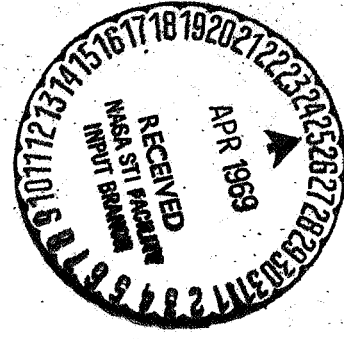


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A AIRCRAFT NOISE

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I. INTRODUCTION

The problem of aircraft noise has become of paramount importance in recent years. This has been due in part to the increased use of commercial and military aircraft, and in part to the tremendous increase in energy of the newer aircraft power plants. This great increase in energy has resulted in noise levels near aircraft which not only exceed human tolerance, but also in many cases cause structural damage and malfunctioning of equipment. The distances over which the noise causes annoyance and interference with conversation have been extended with the result that greater numbers of people are being affected.

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Because greater cost and effort are required to provide for the protection of the occupants of aircraft, the service crews, and the communities near airports, it is of increasing importance to know the characteristics of the various aircraft noise sources, the magnitude of the noise, the nature of the source, and how these characteristics are changed by design and operating conditions.

It is the purpose of this chapter to give a brief description of the nature and sources of aircraft noise from various types of propulsive units, and the theory and equations for calculating the noise intensity and characteristics, when a generally accepted theory is available. For a fuller exposition of the various problems treated, the reader is referred to the references. Some of the references are in themselves surveys of the aircraft noise problem and thus cover certain phases that are not touched on in this chapter.

II. BASIC ELEMENTS

When one considers that aircraft noise sources may have velocities exceeding the speed of sound, and pulsating pressure variations in the order of the ambient pressure, it is somewhat surprising that the linearized theory of small disturbances used in classical acoustics would find useful applications. As a general rule problems that have been successfully treated have been solved by starting from a knowledge of the forces and volume flows usually obtained from aerodynamic

performance information. These forces and volume flows are then represented by acoustic sources of various orders, and the sound field is calculated from a consideration of the equations expressing the radiation properties of these sources. Some of the equations and characteristics of these elementary acoustic sources are reviewed in this section.

The first of these is the simple acoustic source, for which an expression taken from Davis (1) relating the instantaneous pressure at a field point to the rate of fluid emission is

$$p = \frac{i\rho\omega A}{r} e^{i\omega(t-r/c)} \quad (1)$$

where the maximum rate of fluid emission is $4\pi A$. This source is referred to as a volume source.

A second expression relates the instantaneous pressure at any field point to a concentrated oscillatory force $F e^{i\omega t}$. This expression is derived from equations given by Lamb (2) and is

$$p = \frac{F e^{i\omega(t-r/c)} \cos \psi}{4\pi} \left(\frac{i k}{r} + \frac{1}{r^2} \right) \quad (2)$$

ψ is the angle between the force axis and the radius vector to the field point and $k = \omega/c$. It may be noted that Eq. 2 has the directional properties of the acoustic dipole, and is usually referred to as a pressure dipole. For problems in which the field point is several wave lengths from the location of the force, the radiation term is the more important and the second, or induction term, in the last factor may be neglected. There are, however, a number of practical problems in which it is important to know the pressure at a field point very close to the source and for such problems the second term is retained in the calculations.

The magnitude of the pressure due to an oscillating force, having the components F_x , F_y , F_z , moving with uniform rectilinear motion in the positive x direction is given byerrick and Watkins (3) .

$$p = -\frac{1}{4\pi} \left(F_x \frac{\partial}{\partial x} + F_y \frac{\partial}{\partial y} + F_z \frac{\partial}{\partial z} \right) \frac{e^{i\omega(t - \frac{r}{c})}}{S} \quad (3)$$

$$S = \sqrt{(x - x_0)^2 + \beta^2 [(y - y_0)^2 + (z - z_0)^2]}$$

$$\sigma = \frac{M(x - x_0) + S}{\beta^2}$$

$$\beta^2 = 1 - M^2$$

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The field point at x, y, z , and the force located at x_1, y_1, z_1 , are in the same coordinate system moving with uniform rectilinear velocity at Mach number $M < 1$.

In the problems which have been successfully treated, the solutions have generally been built up by use of Eq. 1 to represent volume displacement and by use of Eqs. 2 and 3 for a representation of forces or pressure discontinuities. One of the chief difficulties encountered in the setting up of the problem is to express the aerodynamic forces that produce the noise in terms of these elementary acoustic radiators. A given problem may be represented in various ways, depending on the coordinate system and whether the velocity potential or pressure potential is used. Some comments on this subject are given by Ernsthausen (4) .

The sources that have been discussed have until recently sufficed to deal with most problems encountered. Lighthill has suggested that higher order sources such as the quadrupole and octupole may play an important role in the turbulent jet noise problem. The quadrupole will be further discussed in the section which deal with the continuous jet.

III. PROPELLER NOISE

The noise from a propeller may be related directly to the aerodynamic forces on the blades. These forces may be divided into two broad classes, (1) the steady forces, and (2) the unsteady forces. The steady forces may be conveniently treated as effect of blade thickness, represented by acoustic sources of zero order; and as effects of blade aerodynamic lift, which is represented by pressure dipoles. The noise due to steady air forces is generally referred to as rotational noise. The theory of the noise from the steady forces is quite complete, and it is possible to calculate the absolute intensity, frequency characteristics, and directional properties of the noise directly from a knowledge of the geometry and aerodynamic characteristics of the propeller.

The unsteady forces on the propeller blade also give rise to noise. These unsteady forces may be periodic (integral multiples of the propeller rotation speed) when propellers are operated in unsymmetrical flow conditions, near struts or obstacles, or when blades pass each other in close proximity as in dual-rotation propellers, etc. The unsteady forces may also be of a random nature when the propeller is operating in turbulent air, or when the blade

is shedding vorticity in a random fashion due to viscous effect. Noise associated with this latter phenomenon is generally called vortex noise, as is also the noise produced from vorticity in the wakes of blunt bodies. In addition to these noise sources, unsteady forces may also arise when the blade vibrates or flutters. The theory for noise due to the unsteady forces is rather incomplete. Certain trends can be predicted from theoretical considerations, but the absolute magnitude of the noise can be predicted only on the basis of some empirically determined constants.

A. NOISE DUE TO STEADY AIRFORCES

The predominant source of noise of a conventional aircraft propeller is due to the steady thrust and torque forces on the blades. These forces moving in the propeller orbit produce discrete sound frequencies which are integral multiples of the blade passage frequency. Examples of the frequency spectrum of propeller operating at subsonic and supersonic tip speeds are shown in Fig. 1. These were obtained in the plane of rotation at a distance of thirty feet from a four-foot diameter, two-blade propeller. In each spectrum the first peak occurs at the fundamental blade passage frequency, and the other peaks are integral multiples of the fundamental. For the subsonic propeller the fundamental is most intense, but for the supersonic propeller some of the harmonics are

more intense than the fundamental.

1. Theory for Noise Due to Torque and Thrust

The theory for propeller noise as given by Cutin (6) may be considered in two steps. The first step consists of converting the steady forces which are moving with the blade to oscillatory non-moving forces in the propeller disk. The oscillatory forces are expressed in terms of a Fourier series in time, and for convenience are resolved into two components, one in the direction of the propeller axis, which is designated the thrust component; and the other in the plane of the propeller, which is designated the torque force component. The second step consists of summing the pressures of all the oscillatory forces in the propeller disk in proper phase at a field point. In this step use is made of the pressure field properties of oscillatory concentrated forces as given in Eq. 2.

By making certain simplifying assumptions, namely:

(1) that the observer is far from the propeller, (2) that the airforces on the blades are concentrated at a point on the blade at an effective radius usually taken as 0.8 of the tip radius, and (3) that the blade has no thickness or width, Cutin arrived at the following expression for the root mean square sound pressure of a propeller.

$$p_{rms} = \frac{k}{2\sqrt{2}\pi S_0} \left(-T \cos \delta + \frac{cQ}{\Omega R_e} \right) J_{mB} \left(\frac{k}{R_e} \sin \delta \right) \quad (4a)$$

$$\text{where} \quad k = \frac{m B \Omega}{c}$$

An alternate expression in terms of Mach number M_e of the propeller at effective radius, and power P to the propeller is

$$p_{rms} = \frac{m B M_e}{2\sqrt{2} \pi S_o R_e} \left(-T \cos \delta + \frac{P}{c M_e} \right) J_{mB} (m B M_e \sin \delta) \quad (4b)$$

where m is harmonic number 1, 2, 3; B is number of blades; S is distance from propeller to observer; R effective radius; Ω rotational speed in radians per second; T thrust; Q torque; δ angle from propeller axis to observer (0° in front).

These equations give the far field free space sound pressure for a single rotation propeller operating at zero forward speed. For the case where the observer is near the ground, the pressures are usually doubled to take account of ground reflection.

2. Some Comparison of Measured Noise with Theory

Some comparison of measured noise with the theory have been made by Hubbard and Lassiter (7), and these data for both subsonic and supersonic tip speeds are shown in Fig.2. The measurements were made in the plane of rotation at a distance of thirty feet from a two-blade, four-foot diameter propeller. It may be seen that at a tip Mach number of 0.75 the experiment and theory are in good agreement for the range

of the data presented ($mB = 2.12$). At a tip speed of 1.2 times the speed of sound, there is a reasonable agreement between theory and experiment for the first four harmonics ($mB=2-8$); but for the higher harmonics, the experimental values are considerably below those predicted by Eq. 4. Noise measurements giving the harmonic content of propellers operating at supersonic speeds are still too sparse to warrant any generalization as to the cause of the discrepancies at higher frequencies. It is of interest that the theory predicts a downward trend in sound pressure with harmonic number at low tip speeds and an upward trend for supersonic speeds. The experimental data in general confirms this trend, particularly for the lower harmonics.

3. Directional Properties

Some idealized directional patterns of various components of propeller noise are shown in Fig. 3. Those due to the torque and thrust components as given by Eq. 4 are shown in 3(a) and 3(b) respectively, and 3(c) gives their summation. Directional characteristics of the components due to thickness and vortex shedding are shown schematically in Figs. 3(d) and 3(e).

The theoretical distribution of the sound pressure around a propeller is seen to be a function of the azimuth angle δ . Pressures are zero on the propeller axis, both in front of and behind the propeller since $\sin \delta$ is zero for these positions. Ahead of the plane of rotation the thrust noise is out of phase with the torque noise and subtracts from it; whereas, behind the plane of rotation, they add in phase. Hence, as shown in Fig. 3(c), the noise intensity is a maximum behind the plane of rotation. This maximum occurs approximately ten to thirty

degrees behind the plane of rotation, depending on the tip speed and the predominant harmonics. At the higher tip speeds the maximum intensities are radiated near the plane of the propeller.

In making comparisons between theory and experiment, it has been found that near the plane of rotation where the sound intensities are a maximum, the agreement between theory and experiment has been quite good, as shown in Fig. 2. Near the axis of rotation where the theory indicates very low sound pressures, the experiment generally also shows minima, but the measured values are generally much greater than the theoretical values. These discrepancies are believed to be due to dissymmetry in the flow field and reflections from surfaces near the propeller. If the flow field is not symmetrical, the air forces on the propeller blade are not constant, and one may expect a considerable noise radiated fore and aft of the propeller as indicated in Fig. 3a. In spite of these differences, the theory has been very useful in predicting the approximate direction of the noise intensity, and has also predicted the magnitude of principal harmonics of the noise. The theory has therefore been useful in propeller noise trend studies to show the significant variables in the problem. These are discussed in the following sections.

4. Number of Blades

When the number of blades is increased for a constant thrust and torque, the total noise due to thrust and torque is always decreased. This decrease results from the cancellation of some harmonics of the spectrum and the amount of decrease depends on the strength of the cancelled harmonics. A four-blade propeller having the same thrust and torque as the two-blade propeller of Fig. 1 would have only half the harmonics that are seen to be present in the spectra of Fig. 1. The net result is that all odd harmonics of the two-blade spectrum are cancelled and the amplitude and frequency of the even harmonics are unchanged. Thus, by adding more blades, the harmonics that are not integral multiples of $B\Omega$ are eliminated from the spectrum. A more complete explanation of the physical reasons for this is given by Regier and Hubbard (8). It may be seen that at subsonic tip speeds, the elimination of the first harmonic and all odd harmonics is effective in reducing over-all sound intensity. At supersonic tip speed the over-all noise intensity is not decreased much by the elimination of these same harmonics. In this case there are a large number of important high harmonics of nearly equal intensity, and the elimination of half of them would result in a reduction of only about three decibels.

5. Blade Width

In the theory as given in Eq. 4, the width of the blade is assumed to be zero; hence, one cannot calculate directly the effect of blade width. If one determines how blade width affects the Fourier coefficients of the forces in the propeller disk, one is led to the conclusion that the effect of increasing blade width is to decrease the intensity of the higher harmonics. Some calculated effects of blade width and shape of blade chordwise load distribution on the Fourier coefficients are presented by Regier and Hubbard (8). There is some experimental evidence that a wide blade has a rotational noise of lower harmonic content than a narrow blade. Some questions arise, however, as to the validity of the analysis when the blade width becomes comparable to the wave length of the sound emitted.

6. Power Loading

The effect of power loading may be determined from inspection of Eq. 4b by considering how the sound pressure varies with power and blade radius. If it is assumed that the thrust varies directly as the power, it may be seen that the sound pressure varies directly as the power and inversely as the propeller radius. Hence, for a given power and tip speed it is advantageous, from a noise reduction standpoint, to make

the propeller as large as possible. If one defines the power loading of a propeller as the total power divided by the disk area of the propeller, it can be shown that the ratio of the sound energy radiated to the power into the propeller is directly proportional to the power loading.

7. Tip Mach Number

Although the effect of tip Mach number is implicit in Eq. 4, it is not readily apparent what this effect is because of the complex manner in which the tip Mach number terms enter into the equation. By making use of Eq. 4 and the experimental data of Deming (9), it can be shown that the sound pressure for a given harmonic of a fixed-pitch propeller will vary as a power function of the tip velocity over a wide range of velocities. The value of the exponent n is primarily a function of the harmonic number mB , as shown in Fig. 4 and is different for the near and far field. The far field sound pressure varies approximately from the 5th to the 9th power of the tip velocity depending on the value of the harmonic number mB . Since the sound energy is proportional to the square of the sound pressure, the associated sound energy then can be shown to vary in this case as the 10th to the 18th power of the tip velocity. Mechanical energy required to drive a propeller at fixed pitch on the other hand is proportional to the 3rd power of the tip velocity.

The acoustic efficiency which may be defined as the ratio of radiated sound energy to mechanical input energy is thus proportional to the 7th to 15th power of the tip velocity. Thus, it can be seen that the most effective way of reducing the rotational noise of a propeller is to reduce the tip speed. The radiated sound energy may vary from approximately 1/1000 of 1 per cent of the propeller power at low tip speeds to 1 per cent or more at sonic speed.

Some of the points which have been discussed with regard to Mach number and number of blades are summarized in Fig. 5. Here are shown the sound pressure levels in decibels, calculated by Eq. 4 (sum of first four harmonics) of propellers having different numbers of blades as a function of tip speed. The propeller power is held constant and the free values of sound pressures have been doubled on account of ground reflections. Also shown is the probable vortex noise level which is discussed in another section of this chapter. Fig. 5 is obtained from calculations made by Hubbard and Pegler (10 & 11)

8. Blade Thickness

The effect of blade thickness has been treated by various investigators, notably Deming (12), and Ernsthausen (4 & 13). Although the general approach to the problem has been the same, the assumptions made have been somewhat different. The theory given here will follow that of Deming since it has the same form as Eq. 4, and since it agrees well with the trends of the experimental data of both Deming and Ernsthausen. If one uses the concept of the effective radius as given by Gutin (6), the equation for the root mean square sound pressure due to blade thickness is

$$p_{rms} \approx \frac{k^2 p^2 c^2 B t b R_T}{6 \pi S_0} J_{ms} (k R_e \sin \delta) \quad (5)$$

(Note: In determining the value of the constant $1/6\pi$, it has been considered that only the outer 0.7 of the blade radius is effective in producing noise.) The thickness t and chord b are taken at the effective radius station on the blade ($R_0 = 0.8R_t$).

An examination of Eq. 5 shows that the sound pressure due to thickness of a propeller blade is directly proportional to the total propeller volume, $BtbR_t$. Furthermore, since k appears as a squared quantity in Eq. 5, but only as the first power in Eq. 4, the higher harmonics are more pronounced in the noise due to thickness than in the noise due to torque

and thrust. This is shown in experimental data by Deming (12) in that the Mach number at which the amplitudes of the higher harmonics exceed the fundamental occurs at a tip Mach number of 0.60 to 0.75 for noise due to thickness instead of at a tip Mach number of 0.90 to 1.00 for noise due to thrust and torque. For conventional metal propellers operating at normal angles of attack, the effect of thickness may well be neglected. For propellers operating in flat pitch, the thickness effect may contribute substantially to the total noise, particularly in the higher harmonics.

B. NOISE DUE TO UNSTEADY AIR FORCES

1. Shedding of Vortices

The classical example of noise due to unsteady air forces is the aeolian harp on which sound is produced by wind blowing over strings. The sound in this case is greatly affected by the motion of the strings. Strouhal found that if the strings are not permitted to vibrate, the frequency of the sound is directly proportional to the velocity and inversely proportional to the diameter. (See Aeolian Tones Vol. 1, Richardson, pp 480.) The constant of proportionality is called the Strouhal number.

Stowell and Deming (14) made some tests of rods mounted in a hub and spun in a manner similar to propellers.

They found that the sound energy varied approximately as the 5.5 power of the tip speed and that the predominant frequency increased with the tip speed in agreement with the Strouhal number. The maximum sound intensity occurred on the axis of rotation and the minimum in the plane of rotation as illustrated in Fig. 3e.

An analytical treatment of the noise due to the vortex shedding is given by Yudin (15). He points out that the source of the noise is not the fully developed vortex wake, but the pressure fluctuations on the rod caused by the periodic shedding of vorticity. The predominant forces on the rod are perpendicular to the air flow; hence, for rods spinning in a plane, the direction of the fluctuating forces is parallel to the axis of rotation. Generalizing the problem of spinning rods to propellers and making the assumption that the forces on the blade can be represented by acoustic pressure dipoles of random phase, Yudin obtained a relation for the total sound energy of a propeller due to vortex shedding. He found that if the Strouhal number and drag coefficient do not vary with speed, that the total sound radiated should vary as the tip speed to the 6th power (V^6). Also, if the disturbances on the propeller are in random phase, the sound energy will vary directly as the total blade area of the propeller.

The material presented in the preceding paragraph has been given for insight into how this random noise varies with speed and its directional properties at low tip speeds. There is still considerable controversy concerning the nature and sources of random noise from propellers. This subject is discussed by Kramer (16) and von Sierke (17) particularly for the higher subsonic Mach numbers.

Since the power absorbed by a propeller varies as V^3 and since the vortex noise sound energy varies as V^6 , the acoustic efficiency of vortex noise generation should vary as V^3 . The efficiency of noise generation for rotational noise was shown to vary approximately as V^7 to V^{15} . Hence, at the higher tip speeds the ratio of vortex noise to rotational noise is much less than at lower tip speeds. From a practical standpoint, the vortex noise is of primary concern below a tip Mach number of approximately 0.4. This is particularly true when account is taken of the fact that for low tip speeds the rotational frequencies are generally low, where the ear is less sensitive; whereas, the vortex frequencies are in a range where the ear has maximum sensitivity.

2. Periodic Unsteady Blade Forces

There are cases in which a propeller blade passes obstructions in such a manner that it experiences air forces which are periodic functions of the rotational frequency of

the propeller. This phenomenon occurs for dual-rotation propellers and single rotation propellers operating near air scoops, wings, fuselages, or in a non-uniform velocity field. Pusher type propellers that operate in the wake of wings and struts are particularly subject to forces of this type. If the periodic forces on the blades can be expressed as a function of the blade angular position θ in the propeller disk, the far field pressures may be calculated from an equation given by Pecier and Hubbard (8). This equation based on the same assumptions as used by Cutin is:

$$p_{rms} = \frac{k}{4\sqrt{2}\pi^2 S_0} \int_0^{2\pi} \left(T \cos \delta + \frac{Q}{R_e} \sin \delta \sin \theta \right) \chi e^{-i(mB\theta - k R_e \sin \delta \cos \theta)} d\theta \quad (6)$$

In this equation, T and Q represent the total torque and thrust of all blades as function of the angular position θ in the propeller disk.

C. THE NEAR FIELD NOISE OF A PROPELLER

In the development of Eq. 4 and Eq. 6 for the sound pressures from a propeller, it has been assumed that the pressure which varies as $1/r^2$ in Eq. (2) may be neglected; it has further been assumed that the differences in the distance from the various radiators in the propeller disk to the observer affect the phase of the pressure at the field point but not the magnitude. These assumptions are valid for large distances, but not when the field point is very near the propeller. Hubbard and Regier (18) have extended the analysis of Gutin to include some of the terms which have been neglected in the far field solution. This equation in the form given by Regier and Hubbard (8) is

$$p_{rms} = \frac{1}{4\sqrt{2}\pi^2} \int_0^{2\pi} \left(\frac{T_x}{S_e} + \frac{Q_y}{R_e S_e} \sin \theta \right) \times \left(\frac{i k}{S_e} + \frac{1}{S_e^2} \right) e^{-i(m\theta + k S_e)} d\theta \quad (1)$$

where S_e , the distance between the effective radiators in the propeller and the observer is

$$S_e = (x^2 + y^2 + R_e^2 - 2R_e y \cos \theta)^{1/2}$$

x is the distance ahead of the propeller and
the distance from axis of rotation.

y

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1. Comparison of Near-with Far-Field Noise

Some comparison of the far field and near field propeller noise are shown in Fig. 4 and Fig. 6. These comparisons are based on far field measurements of Deming (9) and Hubbard and Regier (18). It may be noted in Fig. 4 that the variation in tip speed has a greater effect on the far field noise than on the near field noise since the exponent of the velocity is greater for the far field case at any given value of mb . For both near and far fields, the higher harmonics have larger values of the exponent and hence, are more sensitive to the propeller tip speed. Some comparison of the pressures calculated by the far field Eq. 4 with the near field Eq. 7 are made by Hubbard and Regier (18). This comparison is shown in Fig. 6. The ratio of the pressures calculated by the two equations is plotted as a function of distance from the propeller tip to field points in the plane of rotation for the fundamental frequency of a two-blade propeller. The far field equation underestimates the noise to a considerable extent as the field point comes close to the propeller. At a distance of about two diameters from the propeller tip, the agreement of the two formulas is good. Therefore, beyond a distance of two diameters, the far field formula is recommended because of its greater simplicity.

2. Distributed Load Analysis

In the analyses given for the propeller in this chapter, certain simplifications have been obtained by assuming that the entire force on the blade is concentrated at an effective radius R_e . Although the calculations become more involved, one may consider the load distributed over the blade instead of concentrated at the effective radius. Dening (9) has made a comparison for the far field noise using a distributed load as well as an effective radius analysis. He found that the agreement between theory and experiment was not improved much when he used the distributed load instead of the effective radius, and consequently the effective radius analysis has generally been used because of its simplicity.

The effective radius method has also proved useful for near field calculations; however, Hubbard (18) has found that when one considers the pressure very near the propeller, particularly in planes parallel to the propeller disk, that the effective radius analysis does not give as good an agreement with the experiment as does the distributed load analysis. Although Eqs. 6, 7, and 8 are given in terms of effective radius, they may be used to calculate the sound pressure due to a distributed load by considering parts of the blade load to be located at each of several radial stations. The total sound pressure is then obtained by summing the pressures from each of these stations. In making such calculations it is necessary to add the pressures from the several stations in proper phase. In Eq. 9 all the A terms and B terms must be added separately since the A terms represent the real part and the B terms represent the imaginary part of the complex pressure.

D. SPECIAL CONFIGURATIONS

Some unconventional propeller configurations may be found of use for certain special needs such as greater power absorption or for special structural, aerodynamic, or safety considerations. As a matter of interest some of these special types are described briefly along with their noise characteristics.

1. Supersonic Propellers

One means of absorbing a large amount of power in a relatively small diameter is by use of the supersonic propeller; that is, a propeller so designed that a large part of the blade operates at a speed greater than the speed of sound. In contrast to the conventional propeller, its sound spectrum has a high harmonic content. This is illustrated by the lower spectrum of Fig. 1 where several harmonics are seen to be more intense than the fundamental frequency. Not only is the supersonic type propeller a more intense noise source, but its major noise frequencies are in the speech range where the ear has a greater sensitivity. More information concerning some of the characteristics of such propellers are described by Hubbard and Lassiter (7 & 19).

2. Dual Rotating Propeller

The dual or counter rotating propeller is assuming greater importance for the larger powered propulsive units.

Experiments and analysis of noise from such propellers are reported by Hubbard (20). These experiments with four-blade dual configuration have shown that near the plane of rotation, the total noise can be obtained from a summation of the noise fields of its two components. The manner in which the noise fields add up depends on the position of the observer with respect to the direction of the blade overlap. In the direction of the overlap the sound has the magnitude and frequency spectrum of a single propeller having the same number of blades as one stage of the dual. For example, in Fig. 7, along the lines of blade intersection the noise is the same as for a two-blade propeller. In the direction midway between the intersection lines, the sound is that of a single propeller having the same number of blades as the total number of blades of the dual. The over-all sound as function of position about the axis of rotation is shown on the figure.

What this might mean in terms of sound pressure levels may be inferred from a re-examination of Fig. 5. Consider a dual propeller with four blades in each stage. In the plane of blade overlap the noise would correspond to that of a four-blade propeller; whereas, midway between the planes of overlap the noise would correspond to that of an eight-blade propeller.

In addition to the rotational noise of the dual propeller described above, there is a noise associated with the variation

of air forces on each blade as the blades pass each other. The magnitudes of these unsteady forces and the resultant noise from this cause have not been well defined. The noise due to these unsteady forces predominates on the axis of rotation, and although quantitative checks have not been made between theory and experiments, the variation of the measured sound with tip speeds agrees with the theory in Eq. 6.

3. Tandem Propeller

For applications where large amounts of power are to be absorbed, tandem propellers are also being considered. These consist of two separate components having the same thrust axis and the same direction of rotation. The results published by Hubbard (20) would indicate that the noise field from this type of propeller is approximately the same as for a conventional single rotation propeller with the same number of blades and the same angular blade spacing. The over-all noise observed would thus be a function of the phasing of the blades and would be a minimum when they have equal angular spacing. For instance, in the case of a four-blade tandem propeller (two blades in each component) the over-all sound pressure would vary between those for a four-blade propeller as a minimum and those for a two-blade propeller as a maximum depending on the phasing of the blades.

The unequal angular spacing of blades will result in the

cancellation of certain harmonics at the expense of intensifying some of the others. Thus, for some special applications this scheme may be useful in minimizing troublesome beating phenomena. The over-all noise, however, will always be higher for the so-called "x-propeller" than for the conventional type with equal blade spacing.

4. Shrouded Propeller

Since substantial noise reduction is not easy to obtain, and will doubtless entail weight penalties, there is always interest in the use of unconventional methods. Most of the inventions which claim to silence the propeller prove to be misleading and overrated. A device which has some merit and basis for sound reduction is the propeller shroud. A picture of a shrouded propeller is shown in Fig. 7. Munk (21) proposed a shroud as a propeller silencer and thrust augmenter for take-off. He reasoned that a large part of the thrust of a shrouded propeller is the result of suction at the leading edge of the shroud, and that this suction should give thrust with little noise. During some aerodynamic tests it was observed that there was a very marked difference in the sound output of the shrouded propeller, as compared to the unshrouded, particularly for the high speed dual propellers. Some tests were therefore made to study the noise characteristics of shrouded propellers. These are reported by Hubbard (22). It was found that when the shroud was working properly, it was particularly effective in

reducing the higher harmonics of the propeller noise, and that a reduction of about one-half in sound pressure was also obtained for the lower harmonics. However, if the flow was broken down over part of the shroud, the noise could be considerably worse than for the conventional propeller.

E. EFFECTS OF FOR. AND SPEED

A solution for the sound field of a propeller in forward flight at any subsonic speed has recently been obtained by Garrick and Watkins (3). This solution, based on Eq. 3 gives the pressures at any field point, near or far, and represents a generalization and extension of the far field theory of Cutin (6) and the near field theory of Hubbard and Resier (18) to the case of forward speed. It includes as special cases the relation for the static propeller. (Eq. 4 and 7)

The value of the far field pressure is given by the following expression

$$p_{rms} = \frac{k}{2\sqrt{2}\pi S_o} \left[-T \left(M + \frac{x}{S_o} \right) \frac{1}{\beta^2} + \frac{Qc}{\Omega R_e^2} \right] J_{mB} \left(\frac{\frac{1}{2} y R_e}{S_o} \right) \quad (8)$$

$$\beta^2 = 1 - M^2 \quad \text{and} \quad S_o = \sqrt{x^2 + \beta^2 y^2}$$

In this analysis it is assumed that the coordinate system including the field point moves with the propeller in uniform rectilinear motion. Garrick and Watkins (3) show that the

results are also applicable to an observer not moving with the propeller but fixed in space, provided that the proper instantaneous distance between observer and propeller is used. The frequencies heard by the fixed observer will be modified by the Doppler effect; whereas, the moving observer will experience no frequency distortion. The effect of forward speed changes the coefficient of the thrust term, the argument of the Bessel function, and the distance. Some indication of the way in which forward speed affects the propeller noise may be obtained from Fig. 9. At a forward flight Mach number of 0.8, the amplitudes of the higher harmonics are greatly increased compared to the results at static conditions. The effect of forward speed at a constant rotational speed seems to give a similar result as merely increasing the rotational speed at static conditions.

The equations for the *PRESSURES AT ANY DISTANCE*
as given by Terrier and Watkins (3) are

$$p_{rms} = \frac{\sqrt{2}}{4\pi r} (A^2 + B^2)^{1/2}$$

where $r =$

$$A = \int_0^{2\pi} \left\{ \frac{Tx}{S^2} \cos(mB\theta + \frac{1}{2}\sigma) + \left[T \frac{h}{\beta^2} \left(M + \frac{x}{S} \right) - \frac{QmB}{Re^2} \right] \right. \\ \left. \times \sin(mB\theta + \frac{1}{2}\sigma) \right\} \frac{d\theta}{S} \quad (9)$$

$$B = \int_0^{2\pi} \left\{ -\frac{Tx}{S^2} \sin(mB\theta + k\sigma) + \left[T \frac{k}{\beta^2} \left(M + \frac{x}{S} \right) - \frac{QmB}{R_e^2} \right] \cos(mB\theta + k\sigma) \right\} \frac{d\theta}{S}$$

For a field point in the xy plane,

$$S = \sqrt{x^2 + \beta^2(y^2 + R_e^2 - 2R_e \cos \theta)}$$

$$C = \frac{Mx_r S}{\rho^2}$$

Eq. 9 has been used to calculate some trends of pressures as function of flight speed. These are illustrated in Fig. 10, and represent the maximum oscillating pressure in a plane 0.1 diameters from the tin and parallel to the propeller axis.

In these calculations the propeller power has been held constant with the result that the thrust decreases with speed

($TV = \eta P$ where η is the propeller efficiency). As a result of the decrease in thrust with increase in speed, the pressures first decrease. At higher forward speeds this trend is reversed and the pressures increase rapidly, the greatest increase being in the higher harmonics.

IV. NOISE FROM CONTINUOUS JETS

A. STATUS OF THEORY

The stability and noise characteristics of free jets were studied both theoretically and experimentally by various investigators many years ago. An interesting account of this work is related by Rayleigh (23) in a chapter on "Vortex Motion and Sensitive Jets." In this reference it is shown that the interface between two gases moving at different velocities is unstable at all velocities, and that any disturbance in the flow becomes turbulent. Further discussion of the behavior of free jets is given by Richardson in Vol. I, pp 437, of this series. This early work dealt mainly with small, low velocity jets in which the transition from laminar to turbulent flow was occurring in sinusoidal form and with the formation of discrete vortices.

In recent years there has been serious concern about the noise of jets of very high velocities and large sizes with rates of kinetic energies ranging up to 100,000 horsepower in a single unit. Because of the high Reynold's numbers involved, the main point of interest has been the turbulent region of the jet rather than the transition region. The theory for the noise due to turbulent motion and the actual mechanism of its generation is still not well understood. The theory which has received the greatest credence and attention has been

given by Lighthill (5) , and the following sentences are a direct quotation from his summary.

"A theory is initiated, based on the equation of motion of a gas, for the purpose of estimating the sound radiated from a fluid flow, with rigid boundaries, which as a result of instabilities contains regular fluctuations or turbulence. The sound field is that which would be produced by a static distribution of acoustic quadrupoles whose instantaneous strength per unit volume is $\rho v_i v_j + p_{ij} - a_0^2 \rho \delta_{ij}$

where ρ is the density, v_i the velocity vector, p_{ij} the compressive stress tensor, and a_0 the velocity of sound outside the flow. This quadrupole strength density may be approximately in many cases as $\rho_0 v_i v_j$.

The radiation field is deduced by means of retarded potential solutions. In it, the intensity depends crucially on the frequency as well as on the strength of the quadrupoles, and as a result ^{power} increases in proportion to a high/near the eighth, of a typical velocity U in the flow. Physically, the mechanism of conversion of energy from kinetic to acoustic is based on fluctuations in the flow of momentum across fixed surfaces....."

Considerable experimental tests both systematic and ad hoc have been carried out in Great Britain and in the United States on the problem of jet noise and on devices which might affect this noise. This work has been directed toward obtaining a better understanding of the jet and determination of parameters that affect jet noise, both in the near and far field. The relation that the experimental data bears to Lighthill's theory is also one that has received considerable attention.

In the following sections the structure of continuous jets and some of the noise characteristics are discussed. The intermittent or pulse-jet, the ram-jet, and rockets are considered and a simple theory for the noise of a pulse jet is presented.

B. JET STRUCTURE

1. Mixing Regions

Since both theoretical and experimental studies have shown the noise from jets to be related to their flow parameters, a brief description of jet flows will be given. Discussions will be limited to the cases where the jet fluid is discharged into air at rest. Fig. 11 from Kuethe (24) and Alexander, Beron, and Conlins (25), illustrates schematically the regions of the jet that will be referred to in the succeeding discussions, namely: region (a) where the mixing starts,

a transition region (b), and region (c) where the flow is fully developed.

The flow in region (a) is only partly turbulent. A potential core within which the velocity is a constant and equal to the exit velocity extends downstream from the orifice a distance of approximately 4.5 diameters, as shown schematically in Fig. 11. An annular mixing region surrounds this potential core and it is here that the mixing process begins. At increased axial distances the jet broadens out as more air is entrained. Although the jet boundaries are difficult to measure, they have been shown theoretically by Goldstein (26) to have an included angle of approximately 30° . In region (b) the entire jet is a mixing region and the mean flow velocities decrease with increasing axial distance x . This transition region extends from the tip of the potential core to a location approximately 10 diameters downstream ($x/D \geq 10$), after which the flow is believed to be fully developed.

2. Velocity Profiles

A direct comparison of the flow velocities at various locations in an air jet with the velocity at the orifice is given in Fig. 12 by Corrsin (27). On the axis of the jet the velocity remains constant in region (a), decreases rapidly as the axial distance x is further increased, and finally approaches a condition where it decreases inversely as the distance in region (c). The radial velocity profiles vary in shape as a function of axial distance x . Those in region (a) have flat portions where the velocity is constant

and some very steep portions near the edge of the jet. It is in region (a) of the jet that the largest velocity gradients exist. Farther downstream the velocity profiles tend to broaden and the velocity gradients are much lower. In region (c) all velocity profiles are similar. That is, if U/U_{max} were plotted as a function of y/b , (where U is the velocity at any point x, y , U_{max} is the maximum velocity, and b is the width of the jet at the given axial station) all radial velocity profiles would be essentially coincident.

3. Turbulence Profiles

Fig. 13 which is also taken from Corrsin (27) gives some axial and radial turbulence intensity profiles which have been measured with a hot wire anemometer in the same jet for which the data of Fig. 12 were obtained. Turbulence in this figure is defined as u'/U_0 where u' is the axial component of the velocity fluctuations and U_0 is the mean velocity at the orifice. These intensity levels were found in the work of Corrsin (27) to be highest in the vicinity of $y/D = .5$; hence, an axial profile is included at this location as well as at $y/D = 0$. In general, the higher turbulence intensities are associated with the regions of large velocity gradients. These large velocity gradients were shown to occur primarily in regions (a) and (b) of the jet as defined in Fig. 11.

This is believed to be a significant result since there are some indications in recently published work that a large part of the associated noise may be generated in these regions of the jet where the flow is not fully developed. Westly and Lilley (28), Lassiter and Hubbard (29, 30, 431)

- C. TURBULENCE-NOISE CORRELATION

Pressure measurements have been made with a microphone at locations near the jet in an attempt to correlate the near field noise with the turbulence data which were measured inside the jet stream by the use of hot wire equipment. Samples of these data from Lassiter and Hubbard (30 + 31) are shown in Figs. 14-17

Fig. 14 shows a sample axial pressure distribution measured along a line parallel to the 15° - degree jet boundary as shown in the accompanying sketch. These data are for an air jet operating under conditions comparable to those of Figs. 12 and 13. It can be seen that the pressure magnitudes have a low value near the orifice, increase rapidly to a maximum a few diameters downstream and then decrease rather gradually as axial distance is further increased. The shape of this pressure distribution curve is very similar to the axial turbulence profile curves of Fig. 13 and especially

to the curve for $y/D = 0.5$. The maximum pressure values are associated with the region of the jet where the highest velocity fluctuations and hence the highest shears exist. Although no corresponding turbulence data are available for high temperature jets with burning, experiments of Lessiter and Hubbard (30) have shown that the associated maximum pressures occur farther downstream than the data of Fig. 14 would indicate.

Fig. 15 shows some sample spectra obtained by means of a panoramic type analyzer which indicates the magnitude on a logarithmic vertical scale as a function of frequency also on a logarithmic scale. The measured noise spectra, a sample of which is shown in Fig. (15b), are a function of microphone position as well as the size and velocity of the jet, and hence they may vary widely. They are, however, similar in quality to the turbulence spectra for comparable conditions as illustrated in Fig. 15(a). It may be seen that both spectra tend to be random in nature and have a similar frequency content. For purposes of qualitatively correlating noise and turbulence data, the frequencies at which measured spectra such as these tend to peak have been determined from the records and are used in the preparation of Fig. 16.

Fig. 16 allows a comparison of frequencies as a function of jet velocity for noise measured near the jet boundary and for turbulence (axial velocity fluctuations) measured on the center line of the jet and at the same axial station. The frequencies were determined from records such as those described in Fig. 15. It may be seen that the predominant frequency of turbulence increases directly as the velocity increases, as shown by the dashed line. The predominant noise frequency also increases generally as the velocity increases in a manner similar to the frequency variation of turbulence. Comparable noise data for a model jet twice as large indicated that the noise frequencies were approximately one-half those for the one-inch jet of Fig. 15. Jet noise frequencies in the near field appear to be proportional to the exit velocity and inversely proportional to the diameter.

It was of interest also to make similar comparisons at several points near each other and along the fringe of the jet for a constant exit velocity. These latter results are given in Fig. 17 where frequency data are compared at several distances downstream of the jet exit. The noise spectra were measured just outside the jet stream; whereas, the turbulence spectra were measured at points one jet radius from the center line

of the jet and for a velocity of approximately 700 feet per second. Here again the trends are similar and the agreement is good. It may thus be concluded tentatively from the data of Figs. 16 and 17 that the noise is associated in some way with the axial velocity fluctuations in the jet stream.

D. EFFECTS OF VARIOUS PARAMETERS

1. Internal Noise

Experiments have shown that the bulk of the noise from a continuous type jet is generated in the mixing region, external to the nozzle. This noise has a continuous spectrum which contains a wide range of frequencies. In addition to the noise from the exhaust stream of the jet engine, there may be superimposed some components generated by the turbine and compressor elements, the burning processes, and the flow over various appendages in the engine. Some of these latter components may predominate at the low power conditions of the engine but are overridden at the high power conditions by the mixing noise. Lassiter and Hubbard (29), von Gierke, Parrack, Cannon, and Hansen (32).

A qualitative picture of the type of experimental result obtained from two different model test conditions is given in Fig. 18 where sound pressure levels are plotted as a function of jet exit velocity. The solid curve represents the noise measured from the mixing region only, since care has

been taken to minimize all other sources of noise in the apparatus. It is seen that the sound pressure level is a power function of the velocity and the data describe a straight line with a slope of approximately 4. The dashed curve, on the other hand, illustrates the nature of the results when an internal noise source contributes substantially to the total. In this particular case, the internal noise was associated with flow through a throttling valve and did not vary appreciably with exit velocity. It can be seen that the internal noise is the predominant one at the lower jet velocities; whereas, it affects the levels only a small amount at the higher velocities where the mixing noise predominates.

2. Comparison of Near and Far Field Noise

Investigations of the near and far noise fields of the jet by Westley and Lilley (28) and Lassiter and Hubbard (29 + 30) have indicated that for given operating conditions the results obtained are very much a function of the distance of the field point at which measurements are taken. It appears that the mixing region is a volume of noise sources and that different frequencies are associated with different parts of the mixing region. Points in the near field may be considerably nearer one part of the source than another and the resulting pressures

may therefore be quite different as indicated in Figs. 14 + 17. Measurements such as these provide detailed information about the nature and sources of the pressures that are encountered, for instance, by structural components near the exhaust stream. Very little information is obtained as to the pressure levels, frequencies, and directional properties of the noise in the far field.

At large distances the jet appears to be essentially a point source of noise that is quite directional with regard to the frequencies and pressure magnitudes. Fig. 18 has shown that the value of the exponent n is approximately 4. More detailed studies made by Lassiter and Hubbard (30) have shown that the value of this exponent n , varies as a function of distance to the field point as is shown in Fig. 19. The values of the exponent n are plotted in Fig. 19 as a function of distance in diameters for an angle of 90° . At locations in the near field the value of the exponent is of the order of 2.0 or less. The maximum value of 4.0 is obtained at a distance of 150 diameters. Frequency spectra on the other hand seem to be relatively insensitive to changes in velocity in the far field. The work of Hubbard and Lassiter (31).

indicates that the near field spectra are affected considerably by changes in velocity. These results suggest that although the near and far noise fields of a jet are somehow related, this relationship is probably a complex function of distance.

There may be a number of factors that contribute to the difference in the characteristics of the pressures measured near a jet and those measured a 100 or more diameters away. One of these factors has already been mentioned; i.e., the pressures measured near the jet are probably a function primarily of the turbulence that is in the immediate vicinity of the near field point, and the frequency of the sound may well be a function of the rate at which the turbulence is convected past this point. In the far field the sound pressure is probably a function of sound energy radiated from the entire mixing region.

Another factor may be surmised from a consideration of terms which vary as inverse cube and inverse square of the distance in the equation of the pressure from a quadrupole source. The equation of the pressure field of a quadrupole may be obtained by taking the second space derivative of the pressure field of the source (Eq. /).

3. Azimuth of Field Point

The radiation patterns of noise from jets are directional both with regard to the over-all levels and the frequency content. In general, the highest over-all levels are measured to the rear of the nozzle exit and near the boundary of the jet stream. Fig. 20 shows a typical pattern for a turbojet engine at full power, both with and without afterburner.

(Hubbard 33) Sound pressure levels are plotted as a function of the azimuth angle δ which is measured from the jet axis in the front. It can be seen that the measured levels are a maximum at 150° for the basic engine and are a minimum on the axis both ahead of and behind the engine. With afterburner operation, the resulting jet velocities are approximately 40% higher because of the associated higher temperatures. It can be seen that the maximum pressures are measured at a somewhat greater angle in this case. It is believed that this change in the directivity pattern is due to the change in velocity since recent experiments with
(REF 29)
model jets₁ have shown that the maximum radiation occurs at larger angles for higher jet velocities.

In addition to the variation of sound pressure levels as a function of azimuth angles, there are also differences in

the frequency content of the noise. This phenomenon is shown in Fig. 21, where the pressure levels in three frequency bands from Von Gierke et al. (32) are plotted as a function of the azimuth angle δ for a full scale engine. The levels in the 6400-12800 and 12800-25600 cps bands are a maximum at approximately 120° and 135° respectively. For the 75-150 cps band the maximum is seen to occur at 157.5° or more. Thus, the lower noise frequencies tend to radiate in a direction parallel to the jet axis; whereas, the higher ones tend to radiate in a direction perpendicular to it. These results are in agreement with those obtained with model jets.

4. Jet Velocity

The main effect of an increase in exit velocity for a given configuration is to greatly increase the noise levels as indicated in Fig. 18. It follows then, that the most effective method of reducing noise generated in the mixing region is to reduce the jet velocity to as low a value as possible.

It is sometimes helpful to know the total acoustic power that is radiated by the jet. This quantity is related to the total mechanical power in the jet by the curve of Fig. 22 from Von Gierke (17). The percentage of the energy of the jet that is radiated acoustically is plotted as a function of the jet power per unit nozzle exit area for a turbojet engine. The most obvious result is that a larger percentage of energy is radiated at the higher power conditions of the engine. An increase in the jet power is associated in this

case with an increase in the jet velocity, it being approximately proportional to the cube of the velocity.

Similar trends have also been observed for model jets with no burning. Von Gierke (17) indicates that this is a rather general result for various types of jets. It has been noted, however, that the associated acoustic-mechanical efficiencies of cold air jets are lower for a given unit of power than those in Fig. 2.2. There is thus some indication that when burning is present, jets are more efficient noise radiators.

5. Jet Size

At a given field point and for given flow conditions, the noise produced is a function of the size of the jet. Both the frequency content of the noise and its intensity are affected as indicated in Figs. 23 and 24. In the work of Lassiter and Hubbard (27), the over-all noise was measured from circular air jets ranging in diameter from 0.75 to 12.00 inches. Some results of these tests are shown in Fig. 23. Sound pressure levels are plotted as a function of the azimuth angle δ , which is measured from the jet axis in the rear. Data from different jets are shown for a value of Z/D of 16. Here Z is the distance measured from the origin of the jet. Within the scatter of the data, it can be seen that the over-all noise measured for jets of various

Aircraft Noise
by Begier, Hubbard,
and Lassiter

sizes is essentially equal, provided the values of Z/D are equal. It thus follows that the noise at a given field point is directly proportional to the size of the jet for given flow conditions.

6. Frequency Spectrum

Although the spectra from various jets are similar in that they each have a single flat maximum, the frequencies at which these maxima occur vary as a function of the jet size. In general, small jets have a predominantly high frequency content; whereas, large jets have a relatively large low frequency content. Some attempts have been made to systematize the spectra from jets. There is evidence from Mawardi and Dyer (34) and Powell (37) that noise from air jets and turbojets differ mainly as a function of the size of the jet. Mawardi and Dyer have thus proposed that all jet noise may follow a universal spectrum which is described by the empirically-derived curve of Fig. 24. The quantity f_{max} in the figure is defined as the frequency at which the maximum pressure occurs. If f_{max} and the over-all

level in decibels are known, the relative levels at various frequencies may be estimated from Fig. 24. Powell (37) indicates that this frequency f_{max} , is such that the associated wave length is of the order of 3 or 4 exit diameters for fairly high speed jets.

E. CHOKED JETS

1. Noise Characteristics.

Model tests have shown that the noise from a jet is dependent to some extent on its nozzle pressure ratio P/P_0 , where P is the chamber pressure and P_0 is the ambient pressure. If $P/P_0 < 1.88$, the flow in the jet is entirely subsonic and the noise consists only of random components. If $P/P_0 \geq 1.88$, local supersonic flow occurs in the jet mixing region and associated shock formations such as those of Fig. 25 appear. The interaction of these shock waves and the turbulence in the jet stream can under certain conditions generate an additional component of noise by a type of feedback mechanism. This phenomenon was first reported by Powell (35) and a qualitative analysis given by him (36). The effects of this resonance condition are such as to affect both the intensity and the frequency of the noise.

The variation of the over-all sound pressure as a function of nozzle pressure ratio for a given point in the near field is shown in Fig. 26. This is a plot of pressure levels in decibels as observed at a point three diameters downstream and one diameter from the theoretical 150° boundary of a one inch jet. (Lassiter and Hubbard 30)

The vertical dashed line represents the boundary between the subsonic and the overpressured ranges. The pressure levels are seen to increase rapidly throughout the subsonic range and up to a nozzle pressure ratio of about 3.3 in the over-pressured range. At this latter condition the observed pressure magnitudes are much higher than those observed just before choking occurs. A further increase of the pressure ratio results in a sudden decrease of pressure magnitude followed eventually by another more gradual increase at the higher pressure ratios. The large bump in the curve of Fig. 26 is associated with a rather sudden change in the frequency spectrum of the noise as illustrated in Fig. 27. The upper spectrum is associated with unchoked operation of the jet and is typical of spectra observed when the flow is entirely subsonic. Shortly after the critical pressure ratio is

reached, a discrete frequency component of very high intensity appears in the spectrum. The lower part of Fig. 27 illustrates that type of spectrum. Although the effect is not readily apparent because of the different ordinate scales, this intense discrete frequency component occurs in addition to the continuous pressure spectrum and is essentially superimposed upon it.

2. Devices for Reducing Noise

Various methods have been used in order to reduce this component of noise associated with the shock formations in the stream (Westley and Lilley (28), Lassiter and Hubbard (30), Powell (36) and these results are summarized by Powell (37). It has been found that noise reductions can be obtained if the shock waves are weakened or if the jet mixing is made to occur nearer the jet exit. Addition of a gauze cylinder extension to the nozzle, small notches in the exit edge of the nozzle, and teeth which intersect the periphery of the jet stream have been shown to be effective in reducing this noise.

Experiments with cold air jets clearly show the discrete frequency component to be predominant over a part of the nozzle pressure ratio range. Experience with high temperature jets, however, has shown that although the phenomenon can exist under some conditions, it is much less pronounced than for cold air jets.

V. MISCELLANEOUS JET TYPES

A. Pulse-jets

1. Operating cycle

The pulse-jet was first used in quantity by the Germans to power the V-1 missile. It is now used primarily as a source of power for helicopters, and in that capacity it offers several advantages. Among these are its simplicity of operation and the large thrust-to-weight ratio obtainable with it. In operation of this type of engine, air is drawn into the combustion chamber through shutter-like valves at the forward end, and through the tail pipe, and is mixed with fuel. Combustion raises the chamber pressure sufficiently to force the valves closed and thereby permits the exhaust gases to escape only through the tail pipe to produce thrust. This cycle is repeated periodically at the resonant frequency of the tube-chamber configuration, which is in the order of 100 cycles per second for an engine having a six inch exit diameter. The operation of the engine is basically an acoustic phenomenon, since the firing is controlled by the tube resonance.

2. Noise Characteristics

As might be expected from the periodic nature of the combustion process, the predominant noise from a pulse-jet is composed of discrete frequency components which are harmonics of the firing frequency. For example, figure 28 illustrates a sample pulse-jet noise spectrum from an engine rated at 20 pounds thrust and operating at 30% of the

rated value. This particular spectrum was obtained by Lassiter (38) at a distance of 20 nozzle diameters from the engine and at an azimuth angle of 90° . For these conditions the noise is seen to be almost entirely due to the single discrete component at about 120 cps. The total pressure wave form at the right of the figure reflects this single frequency predominance, also since it does not depart greatly from a sinusoid.

This tendency for the fundamental Fourier component of the noise to be strongest is generally true at all points in the sound field; although at angles close to the thrust axis, some of the harmonics assume greater proportions. Some experiments reported by Veneklasen (39) show that when a pulse-jet is operated at full power the fundamental firing frequency decreases somewhat and the amplitudes of the first few harmonic of the firing frequency are nearly equal to the amplitude of the fundamental. Thus, in the spectrum of an engine operating at full power, the fundamental may not play as important a role as it does at partial power, which is the condition illustrated in Fig. 28.

The angular distribution of the sound level of the fundamental frequency from a six-inch pulse-jet operating at its rated 90 pounds of thrust is shown in Fig. 29. The curve shown relates to a distance of 20 nozzle diameters from the engine tail pipe. The pressures are highest toward the rear of the engine, being of the order of 140 decibels

3. Theory

The fact that the fundamental frequency is usually the strongest component in the pulse-jet noise spectrum suggests that the operating cycle might be approximated by a steady flow velocity and a superimposed sinusoidal velocity at the fundamental firing frequency. Since the wavelength of sound at the fundamental frequency is large compared to the engine tailpipe diameter, an approximation to the acoustic energy radiated can be made from a consideration of the sound pressure from a simple source (Eq. 1). Lassiter(38) and Powell (40), have independently used such an analysis. The essence of this analysis is outlined below and a comparison with an experiment is given.

The total power E radiated from a simple source of strength Q is

$$E = \frac{\pi \rho f^2 Q^2}{2c} \quad (11)$$

where Q is the maximum rate of volume emission from the source, ρ the density, f the frequency, and c the speed of sound (Morse 41). In calculating the sound energy from a pulse-jet, the quantity Q is set equal to the product of the oscillating velocity at the exit and the area of the tail pipe. The oscillating velocity is assumed to be equal to $1/2(U_{\max} - U_{\min})$. An approximation to the values for $U_{\max}$ and $U_{\min}$ can be made by assuming that the tailpipe is

overpressured or choked, both on exhaust and intake. This leads to values for velocity that are sonic in each case but U_{max} will be sonic at the temperature of combustion and U_{min} will be sonic at a temperature near ambient.

An interesting comparison between calculated and measured total radiated sound power can be made for an engine rated at 90 pounds of thrust. The simplified theory indicates a total radiated power of 8.1 kilowatts, as compared with a value of 11.6 kilowatts obtained from the measured data.

Although the total radiated acoustic power as calculated from simple source theory is within 2 decibels of the measured value, the pressure distribution in space deviates considerably from the uniform distribution of a simple source. This is demonstrated in Fig. 29 which shows that the sound is strongly directional toward the rear of the engine. There are a number of reasons why the pulse-jet sound pressure distribution might be expected to deviate from that of the simple source. Some of these are as follows: (1) The engine is not a single-ended source but contains a secondary source at the intake. (2) The particle velocities at the jet exit are of the order of sonic speed velocity. (3) There is a periodic flux of momentum directed toward the rear of the engine resulting in a periodic force.

These considerations suggest that dipole and perhaps higher order sources should be considered in the theory of the sound pressure field of a pulse-jet engine. An analysis using only the simple source does serve a useful purpose in that it may be used to estimate the total radiated power.

B. PAM-JETS

This type of engine, in contrast to the pulse-jet, is a steady flow device which depends on the ram velocity of forward speed to effect compression of the intake air prior to combustion. As such it would be expected to produce noise comparable to that of a turbojet engine as indicated by von Glarke (17) and Bolt, Beranek, and Newman(42). This type of engine is subject to certain instabilities which may cause it to operate in such a manner that the nature of its noise is radically *CHANGED*. Instead of the random spectrum usually associated with steady-flow jets, the spectrum may contain several strong discrete components which are shown by Lassiter (38) to be harmonically related. This change in nature of the noise is associated with rough burning and is apparently due to an unstable flow state or to some type of combustion instability.

The noise spectrum of a rough burning subsonic ram-jet of a type used for helicopter rotor propulsion is shown in Fig. 30 from the work of Lassiter (38). The engine was

operated at 80% of its rated thrust of 28 pounds. The spectrum clearly shows the presence of a few discrete harmonic components, some of which are of larger amplitude than the fundamental. This particular spectrum was obtained at a distance of 26.7 nozzle diameters from the engine and along the 90° azimuth, but it is also typical of the spectra at other angles.

Measurements made by Lassiter indicate that the over-all sound pressure levels at this operating condition are comparable to those of a pulse-jet for the same thrust. The angular distribution is also very similar to that of the pulse-jet fundamental frequency in Fig. 29 .

C. ROCKETS

Rocket engines are used mainly for propelling missiles at high speeds and for thrust augmentation of aircraft. Since the exit gas velocities are supersonic, the associated noise levels are relatively high. Very few systematic noise measurements are available for either solid fuel or liquid fuel rockets and hence few generalizations can be made at this time.

The data of von Gierke (17) and Lassiter and Heithotter (42) indicate that the noise is of a random nature and the spectra are similar to those of subsonic jets. Fig. (31) from the work of Lassiter and Heithotter gives spectra at azimuth angles θ of 15°, 90°, and 135°

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from a solid fuel rocket engine rated at 1000 pounds thrust. The peaks of the spectra are seen to differ as a function of azimuth angle as for subsonic jets but these frequencies are generally lower than might be expected on the basis of subsonic jet experience which is summarized in Fig 24 . It is also of interest to note that the spectrums of three different sizes of solid fuel rockets measured by Lassiter and Heitkotter (43) did not vary systematically with nozzle size.

The angular distribution of the over-all sound pressure of a rocket engine as shown by Lassiter and Heitkotter (43) is similar to that of a high velocity subsonic jet. This radiation pattern has its maximum values at an azimuth angle of approximately 135° .

VI. OTHER SOURCES OF AIRCRAFT NOISE

A. AERODYNAMIC NOISE

Aerodynamic noise is generated in the boundary layer of the airplane as it moves through the air. It has a continuous type spectrum which includes components throughout the audible range and also in the ultrasonic range. This noise will probably not be of concern to observers outside the airplane since it is an important consideration only at high flight speeds and apparently does not radiate appreciably to the surrounding air.

Data on the aerodynamic noise in the passenger compartment of a large glider from the work of Rogers (44) are shown in Fig. 32 where sound pressure levels are plotted as a function of the air velocity. The sound pressure levels are seen to be a power function of the air velocity with the exponent being approximately 2.5. Data obtained in various types of aircraft by various investigators indicate that this exponent applies approximately throughout the subsonic flight range for a variety of aerodynamic shapes. The sound pressure levels at a given velocity, however, may be higher for poor aerodynamic shapes and will vary in accordance with the sound transmission and absorption characteristics of the fuselage. It was also found in related tests by Rogers that the energy in the noise spectrum tends to shift to the higher frequencies as the air

velocity increases. For velocities in excess of 400 miles per hour, the highest levels have been measured in the frequency range of 1200-2400 cps for a current fighter type airplane.

Conventional methods of sound proofing will probably be adequate for protection from this type of noise since the bulk of the sound energy, particularly at the higher flight speeds, appears to be in the frequency range where sound proofing is effective. It is also particularly important to have adequate seals around windows, doors, canopies, etc., since faults of this kind which allow airflow into the airplane may markedly increase the noise level. Pressurized cabins are especially effective in minimizing aerodynamic noise since all leaks are effectively sealed.

3. RECIPROCATING ENGINES

The main source of noise from the reciprocating engine is the exhaust. The sound pressure levels vary as a function of the type of manifold used, and for a given type of engine it has been estimated by *Rudmose* and *Beraneck* (45) that the sound energy varies as the power. Doubling the power increases the noise 3 decibels. When reciprocating engines drive aircraft propellers, the noise in some instances is of the same order of magnitude as from the propeller. Propeller noise levels are generally higher in present day

aircraft for take-off, climb, and cruise conditions as indicated by McFarland (46) ; although in some instances, the exhaust noise may be more objectionable. When some provision has been made to quiet the propeller as in the work of Vogely (47) and Beranek et al. (48) , the exhaust noise must also be reduced in order to achieve effective over-all noise reduction. If stub exhausts are used for reasons of performance, the exhaust noise levels may be somewhat higher than if the collector-ring type of manifold is used. Substantial noise reduction may be achieved by passing the exhaust through a turbine. The turbine may be used to drive a supercharger, or be geared into the engine as in the compound engine. Such a scheme results in fuel economy as well as in noise reduction.

Fig. 33 gives the sound pressure levels in various octave bands of the exhaust noise measured by Stokes and Davis (49) at a distance of 200 feet from a 190 horsepower aircraft engine. The firing frequency was approximately 1300 cps in this case and the highest levels were recorded at that frequency. The spectrum is seen to contain mostly low frequencies and drops off rather rapidly with increasing frequency. Although it is recognized that there is some noise associated with the high velocity exhaust gas streams, this component of noise is seen to be much lower in level than the discrete low frequency components.

McFarland (46) estimates that other noises from the engine are usually approximately 10 to 15 decibels below the level of those from the exhaust. These consist primarily of the clatter of valves, gears, carburetor, supercharger, and other accessories.

C. SONIC BANGS

1. High Altitude Maneuvers

The sonic bang is a popular term used to describe the explosive sounds that are often heard on the ground when aircraft are maneuvering at transonic speeds. A graphical description of the physics of sonic booms was given by Prandtl (50) in 1938. Since that time a number of investigators have discussed the subject in considerable detail. Among these are Lilley et al. (51), Walters (52), and Warren (53).

A simple illustration of the generation of a sonic bang is given in Fig. 34. An aircraft which is now at A has created disturbances at B, C, D, E, etc., while traveling in a straight line uniformly at the speed of sound. Waves travel in all directions from the disturbance point also at the speed of sound, and in the direction of motion these wave fronts tend to congregate to form a shock wave. The pressure discontinuity represented by the shock wave will continue to travel in the same general direction indicated on the figure

even though the aircraft then changes speed or direction. An observer in the proper location will then experience this pressure discontinuity as the sonic bang phenomenon. At supersonic flight speeds, the same phenomena occur but are observed most readily at some acute angle to the line of flight.

The theoretical work of Lilley et al. (51) indicates that for airplanes in level supersonic flights at altitudes of 30,000 feet or more, the pressure levels at the ground will be in the order of 0.5 lb. per sq. ft. These values may be expected to increase for lower altitude operation and may be higher as a result of maneuvers than for level flight. No lasting physiological effects have been reported by observers exposed to this type of noise although an inexperienced observer is frequently frightened by it and the associated rattling of windows and vibration of buildings.

2. Low Altitude Supersonic Flight

The discussion thus far has been concerned mainly with sonic bangs generated in maneuvers at high altitudes, or level flight at high altitudes. As the performance of aircraft is improved so that sustained level supersonic flight near the ground is possible, the possible destructive power of the sonic bang assumes different proportions. Some of these possibilities are discussed by Doughlin (54).

To understand these potentialities, one must realize that the weight of an aircraft is supported ultimately by the earth. When an airplane flies at subsonic speeds, this weight is distributed over a very large area. The pressures are small, and the pressure gradients are so low as to be indistinguishable from barometric fluctuations due to other causes. When the airplane flies at supersonic speed near the ground, the weight of the airplane is concentrated in a much smaller area; hence, the pressures are much greater, and the pressure variation with time is discontinuous as the shock front passes over the observer. Some of these points are described and illustrated in more detail by von Karman (55). If the airplane flies at supersonic speed near the ground, the ground pressures approach the pressures on the wing and therefore pressures exceeding 100 pounds per square foot are possible. If serious damage is to be avoided, supersonic flight must be restricted to uninhabited regions or to high altitudes.

VII. COMPARISON OF NOISE LEVELS FROM VARIOUS AIRCRAFT PROPULSIVE SYSTEMS

The previous sections of this chapter have dealt with the nature and sources of aircraft noise and have indicated some of the parameters that are important in noise generation. Fig. 35 has been prepared to indicate the magnitudes of the noise level variations which one can expect from changes in design or operating conditions, and in addition to indicate the noise levels that are anticipated for some future designs. This figure is based on noise data gathered from several of the references of this chapter. Those data have been extrapolated to conditions corresponding to 10,000 pounds of thrust and an observer's distance of 300 feet. The resulting estimated maximum noise levels are plotted in the form of a bar chart. This chart represents only those levels in the direction of maximum radiation. Although no attempt is made here to compare these noise sources on the basis of total radiated power, some rather comprehensive studies along these lines are given by Bolt, Beranek, and Newman (42).

Although care must be used in comparing those units which have widely different directional patterns, certain conclusions can be drawn from Fig. 35 and other related studies. For instance, for the same power delivered to the

propeller, the exhaust noise level appears to be lower for a turbo-propeller engine than for a reciprocation engine. For turbo-propeller units designed so that the propeller contributes 80 per cent of the total thrust, the propeller noise will probably be the main component even when the so-called "quiet" propeller is used.

Noise levels for the three following propellers, differing mainly in tip speed of operation, have been shown in Fig. 22 for comparison: (1) the low tip speed propeller, $M_t = 0.60$, (2) the conventional propeller, $M_t = 0.80$, and (3) the supersonic type propeller which by definition operates with some of its blade sections at supersonic speeds. Rather large variations in noise levels may be obtained from these variations in tip speed as previously indicated in Fig. 5. For instance, during static testing of supersonic type propellers under certain atmospheric conditions, complaints were received from as far away as 10 miles.

Jet noise is recognized to be largely a function of jet exit velocity. This result is also illustrated in Fig. 35 by a comparison of the noise from a turbojet engine with the levels estimated for other jet engines having both lower and higher exit velocities. The by-pass engine operates in such a manner that part of the air from the compressor is ducted around the burners and is exhausted along with the hot

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gases. This type of engine has lower average exit velocities than a turbojet engine and also has lower associated noise levels.

When afterburning or "reheat" is used in a turbojet engine, extra fuel is burned in the tailpipe and the exhaust gas temperatures may be essentially doubled. The resulting exit velocities and noise levels are correspondingly higher than for the basic engine. Rocket engines operate with supersonic exit gas velocities and are thus inherently more noisy than other jets discussed.

The noise from a reciprocating engine helicopter is due mainly to the engine exhaust and accessories with the rotor playing a secondary role. In the case of rotor tip propulsion by means of units as the pressure jet or pulse jet, the over-all noise of the helicopter will increase considerably, with the noise levels becoming comparable to other aircraft systems producing the same thrust.

This chapter has discussed some of the physical characteristics of various aircraft noise sources, and the material presented has been taken largely from references (1-55). Many additional references are available which are of interest. The nature and sources of aircraft noise are further discussed in references (56-75) with special emphasis on moving sources (68-71), and noise due to turbulence and shock wave interaction (72-75). References (76-93) deal with other physical aspects of the problem such as (1) sound propagation (76-79), (2) sound treatment for aircraft (80-84), (3) mufflers for reciprocating engines (85-87), (4) mufflers for jet engines (88-92), (5) sound treatment for wind tunnels (93), (6) acoustic screening for airports (94), and (7) operational considerations (95-98). Finally, references (99-104) indicate the nature of some of the physiological and psychological aspects of the problem.

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SYMBOLS

GENERAL

p	sound pressure
ρ	fluid density
c	speed of sound
t	time
ω	angular frequency of sound
	angular velocity of the propeller
k	ω/c
$\dot{m}A$	rate of fluid emission
F	magnitude of concentrated force
ψ	angle between force direction and radius vector to field point
r	distance from source
F_x, F_y, F_z	force components
M	forward Mach number
β	$1 - M^2$
S	distance

PROPELLER

x, y, z	rectangular coordinates of observer or field point, x is distance from plane of propeller, positive in front, y and z are distances from propeller axis
δ, S_0	polar coordinates of observer or field point, δ is measured from front of propeller axis, S_0 is distance from observer to propeller center
θ, R_0	polar coordinates of pressure doublet in propeller disk, θ is measured from y -axis; R_0 , the effective radius, is generally taken as 0.8 of propeller tip radius

S_e	distance from effective-radius station to observer or field point
M_e	rotational Mach number of effective-radius blade section
M_t	rotational Mach number of blade tip section
V	blade section velocity
V_e	velocity of effective-radius section
V_t	blade tip velocity
R_e	effective propeller radius
b	blade chord
D	propeller diameter, jet nozzle diameter
B	number of blades
P	power to propeller
Q	propeller torque
T	propeller thrust
m	order of harmonic
δ	azimuth angle
n	exponent of velocity
d	distance in radial direction from propeller tip to field point
$J_{m3}(Z)$	Bessel function of order $m3$ and argument (Z) , where $Z = m3U_0 \sin \delta$
θ	angular position of blade in propeller disk
	<u>JET</u>
v_i, v_j	velocity vectors
P_{ij}	compressive stress tensor
a_0	sonic velocity in medium ambient to jet

u	typical velocity in jet flow
D	nozzle diameter
b	width of jet at a given axial station
Z	distance from center of nozzle exit-face to field point or observer
x	axial distance, positive rearward
y	radial distance from jet centerline
U	mean velocity of jet flow at a given point
U_0	mean jet velocity at nozzle
U_{max}	centerline mean velocity at a given axial station
u'	root-mean-square velocity of axial turbulence component
f_{max}	frequency of maximum pressure level
C	number proportional to quadrupole strength
P	static pressure in jet settling chamber
P_0	ambient static pressure
Q	maximum rate of volume emission from simple source

-4-

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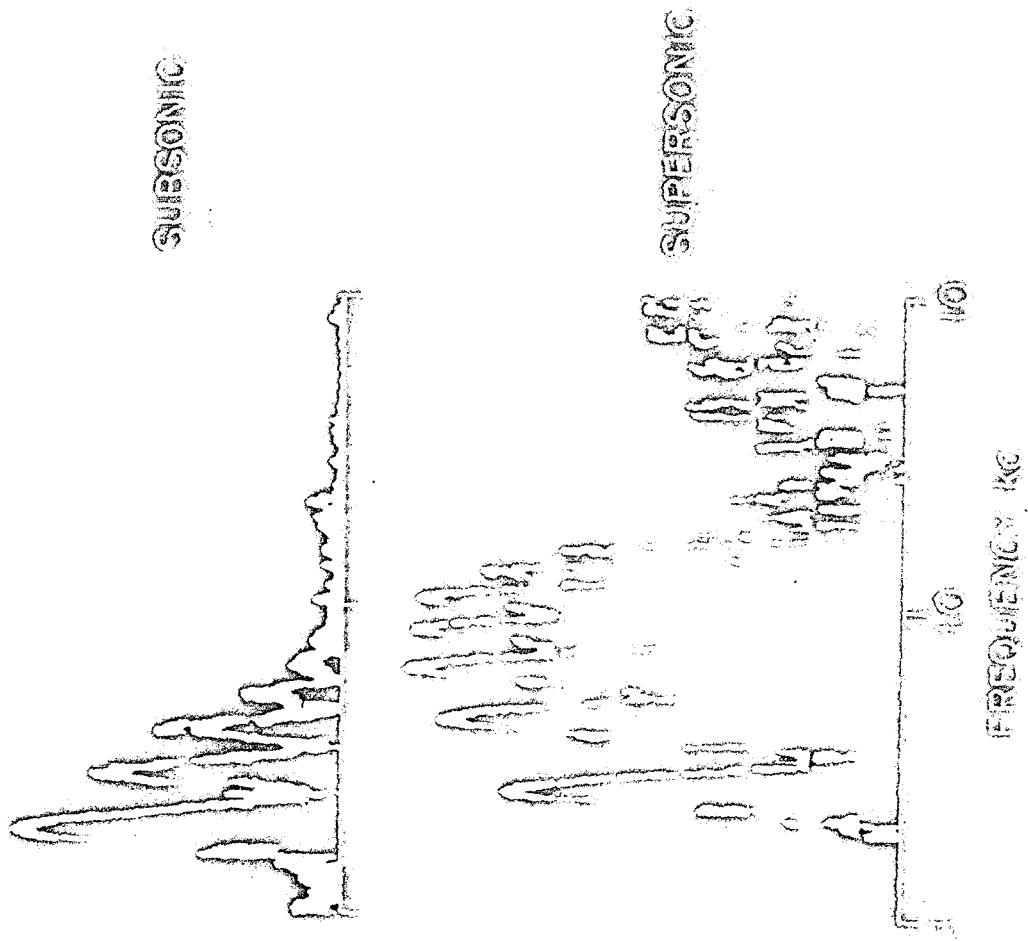


Figure 1. Typical spectra for subsonic and supersonic flow.

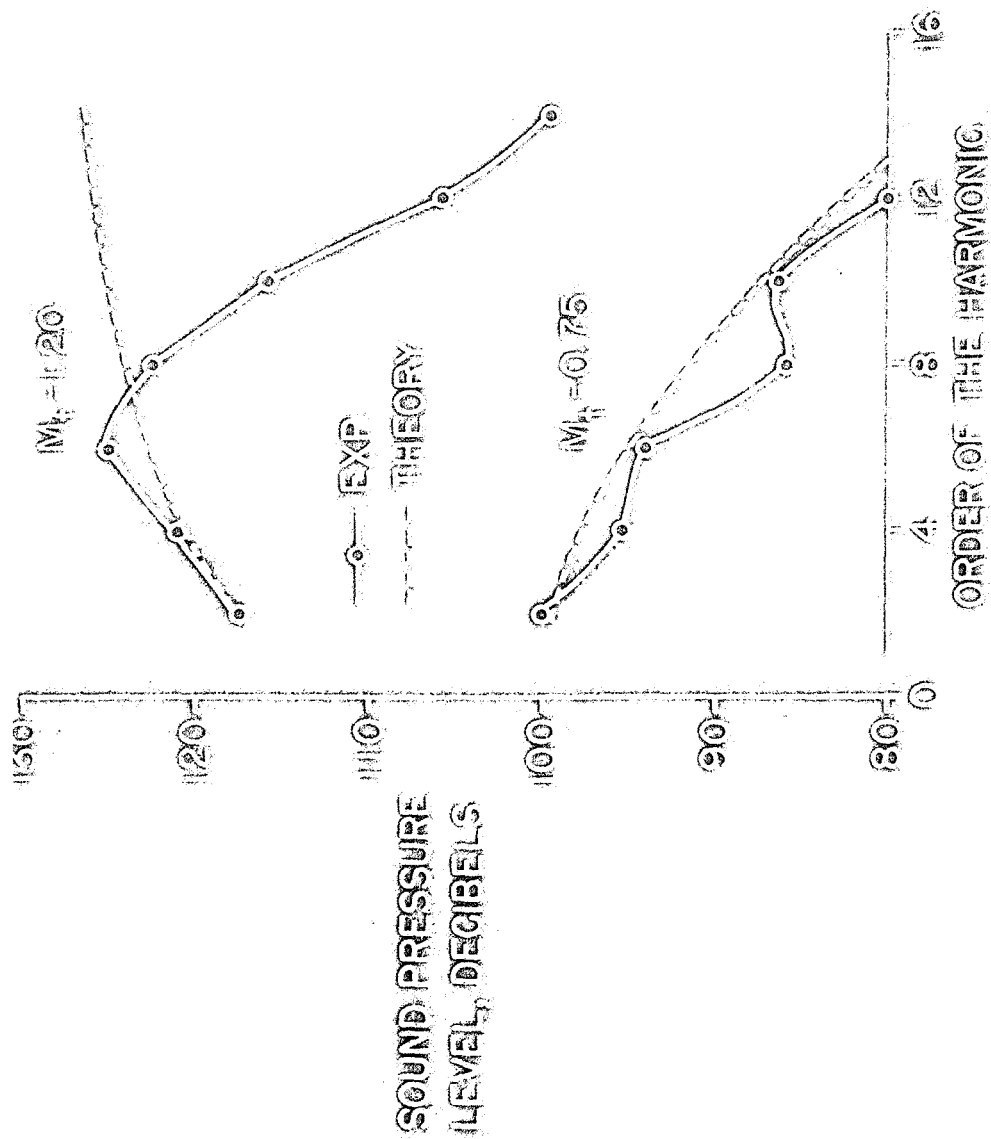
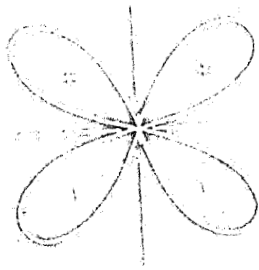
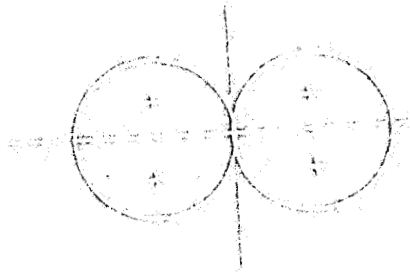


Figure 2. Comparison of experimental and theory for propeller sound pressure levels at subsonic and supersonic tip speeds. (Data courtesy of Dr. Theodore G.)

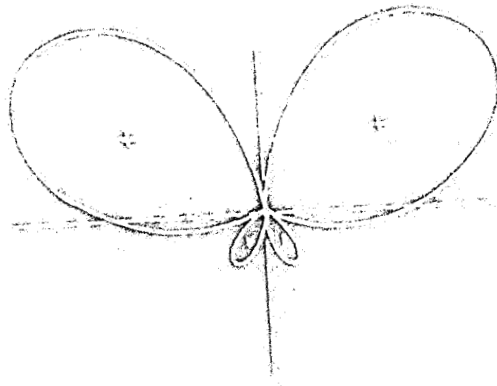
Plane of rotation
 motion is
 parallel
 axis of
 rotation



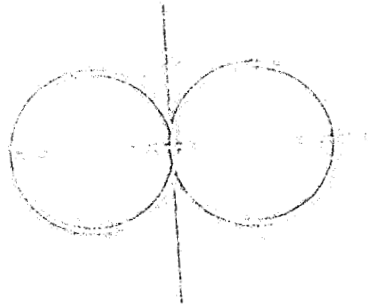
(a) Torque



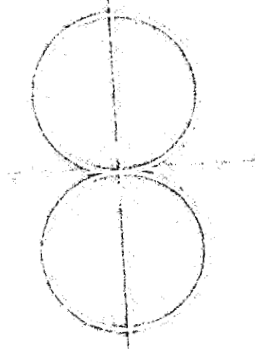
(b) Torque



(c) Torque and Torque



(d) Torque



(e) Vortex shedding

Diagram (a) shows a cross-section of a rotating body with a central point and four lobes. Diagram (b) shows a cross-section of a rotating body with a central point and two circles. Diagram (c) shows a cross-section of a rotating body with a central point and two large lobes and two smaller lobes. Diagram (d) shows a cross-section of a rotating body with a central point and two circles. Diagram (e) shows a cross-section of a rotating body with a central point and two circles.

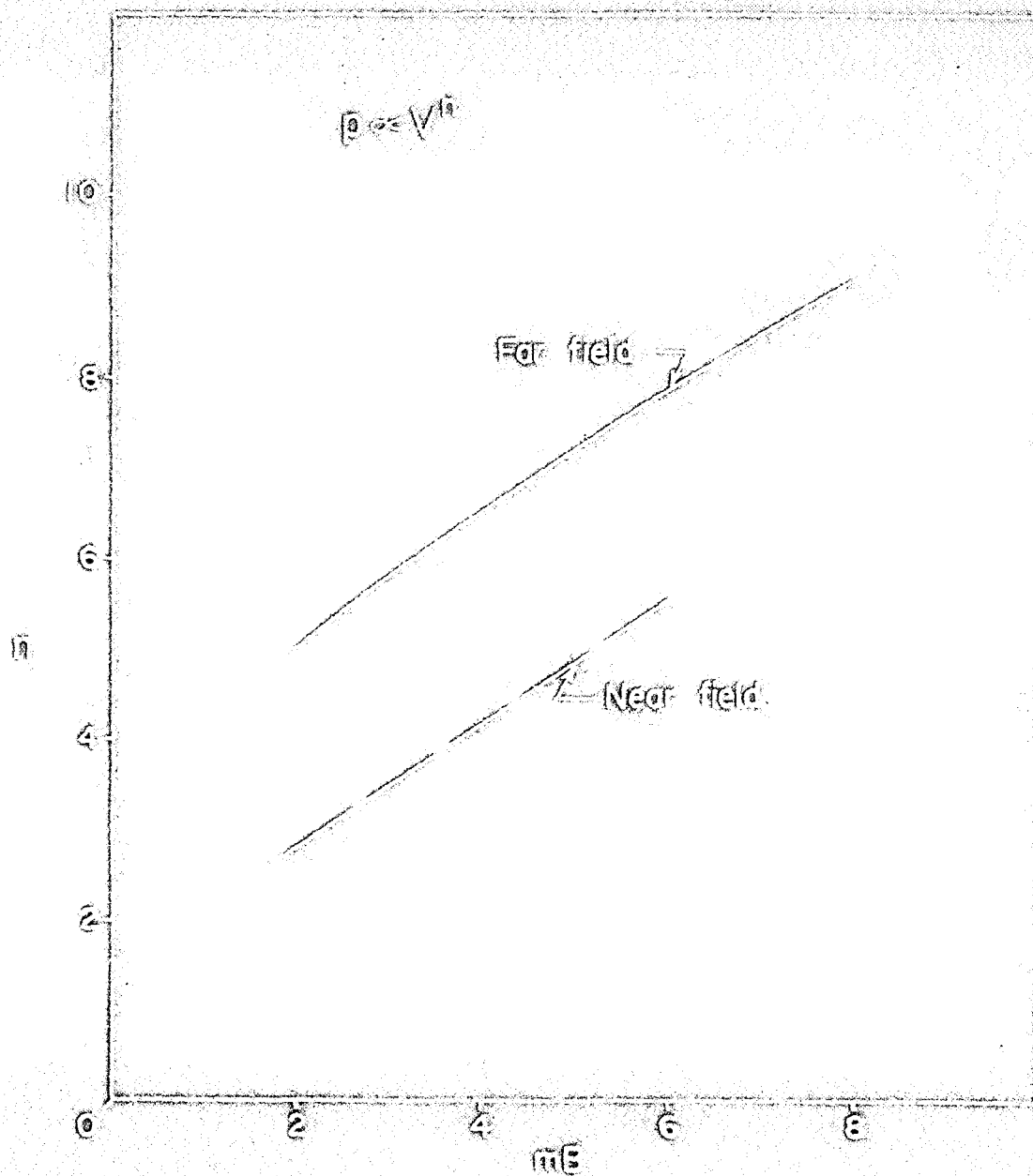


Figure 12: Effect of resonant modes on the exponent n for the near and far field sound pressure of a propeller. (Data obtained from acoustic tubes 1 and 16.)

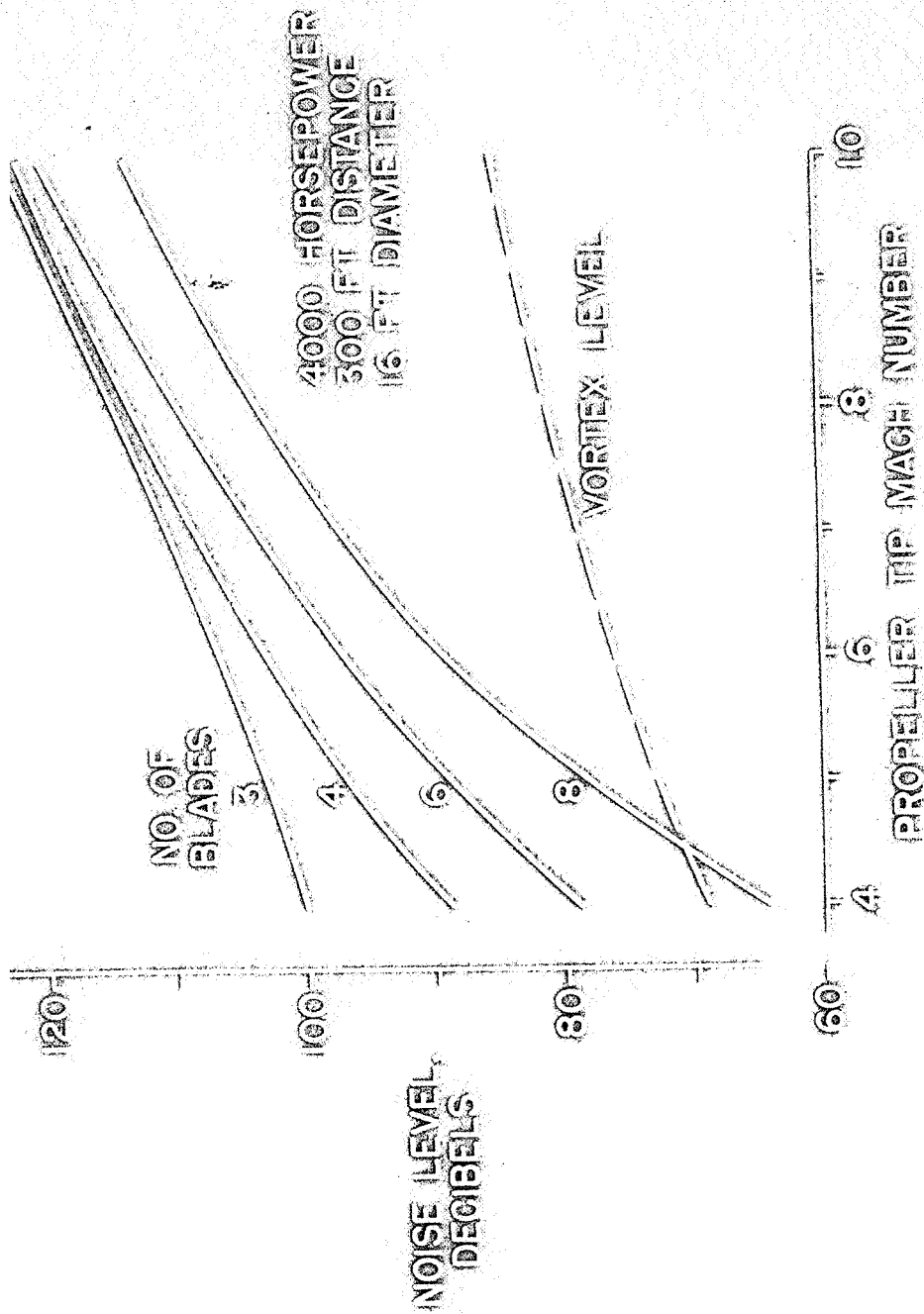


Figure 5. Effect of number of blades and propeller tip speed on the noise level in decibels for a constant power input. Data obtained from references 10 and 11.

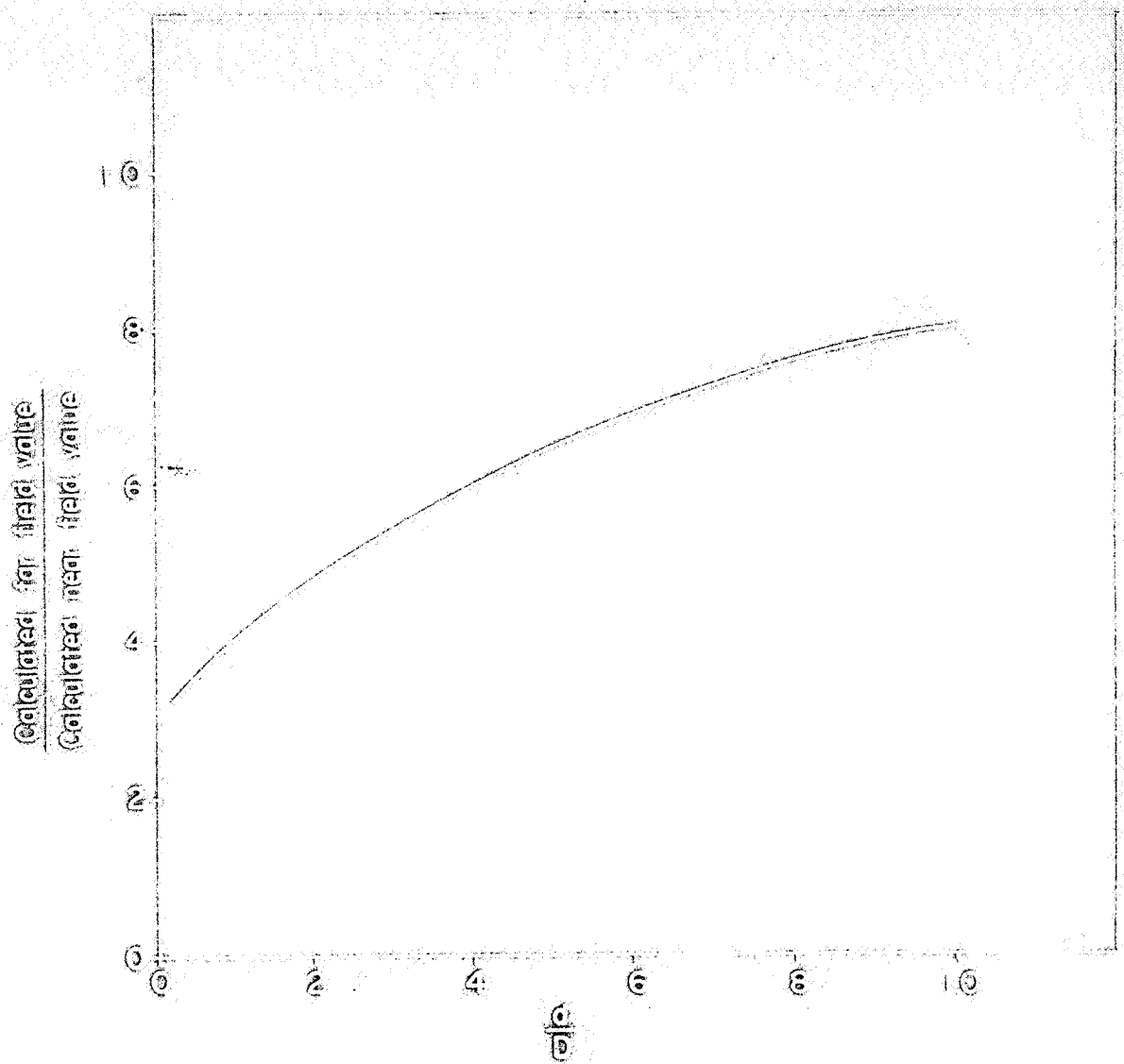
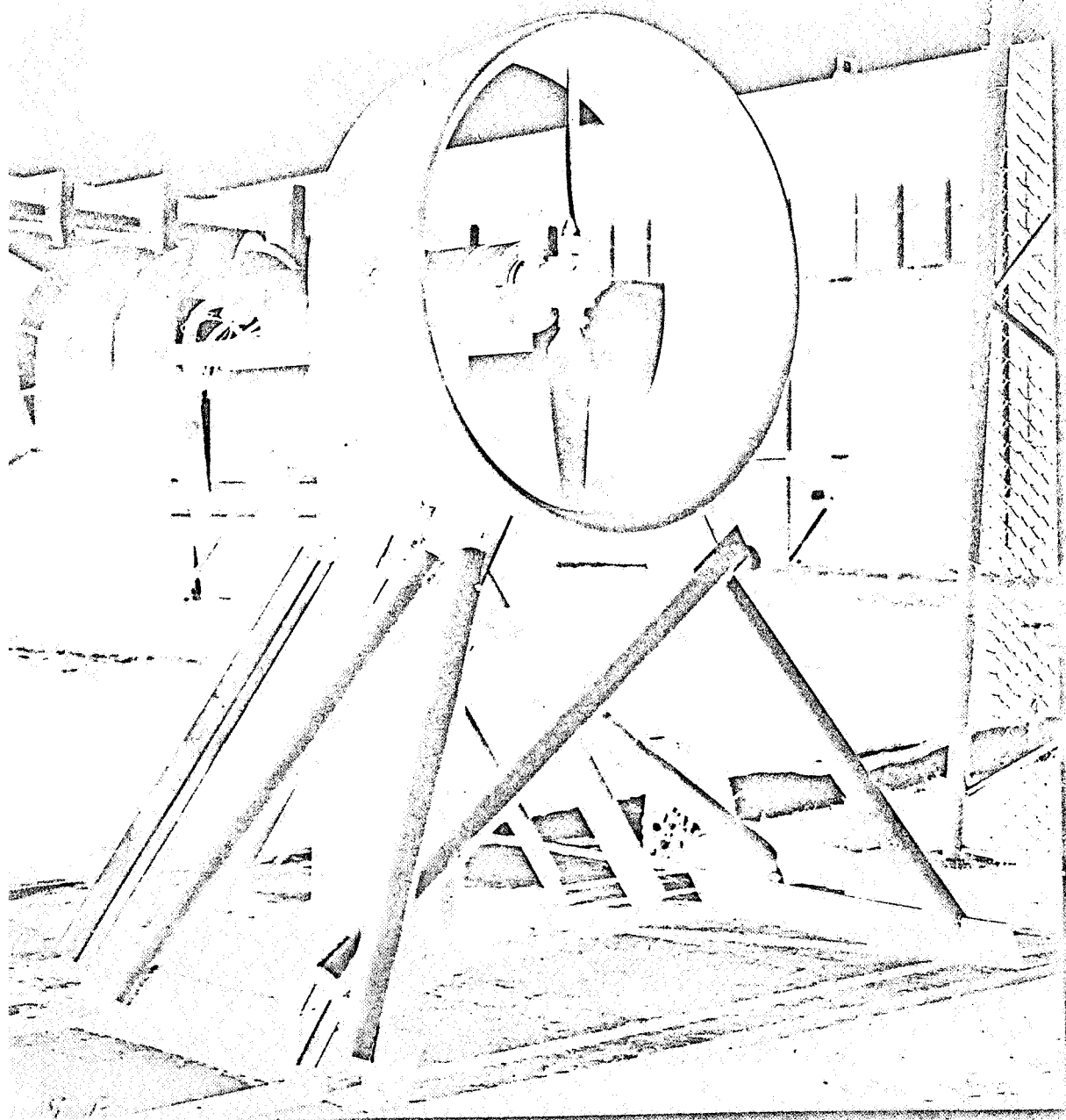


Figure 6c Comparison of calculated values of near and far field pressures for the fundamental frequency of a three-blade propeller in the plane of rotation, $M_\infty = 1.0$. (Data obtained from reference 15.)



[Faint, illegible handwritten notes]

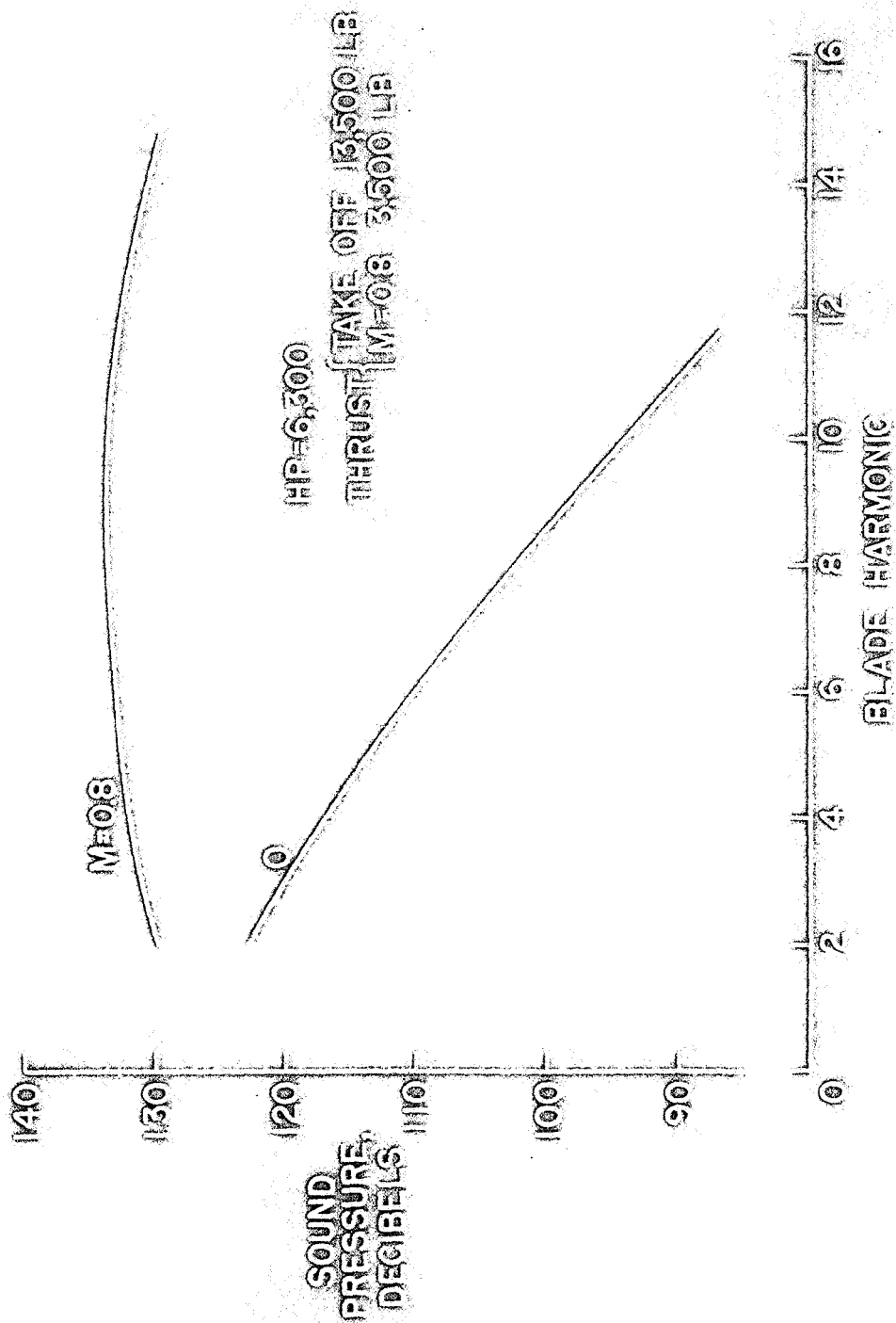


Figure 2. Comparison of the calculated air field sound pressure levels for various propeller harmonics at a constant Mach number of 0.8. The comparison is valid for the two sound spectra, 6/70 2-10, 10/70 2-10.

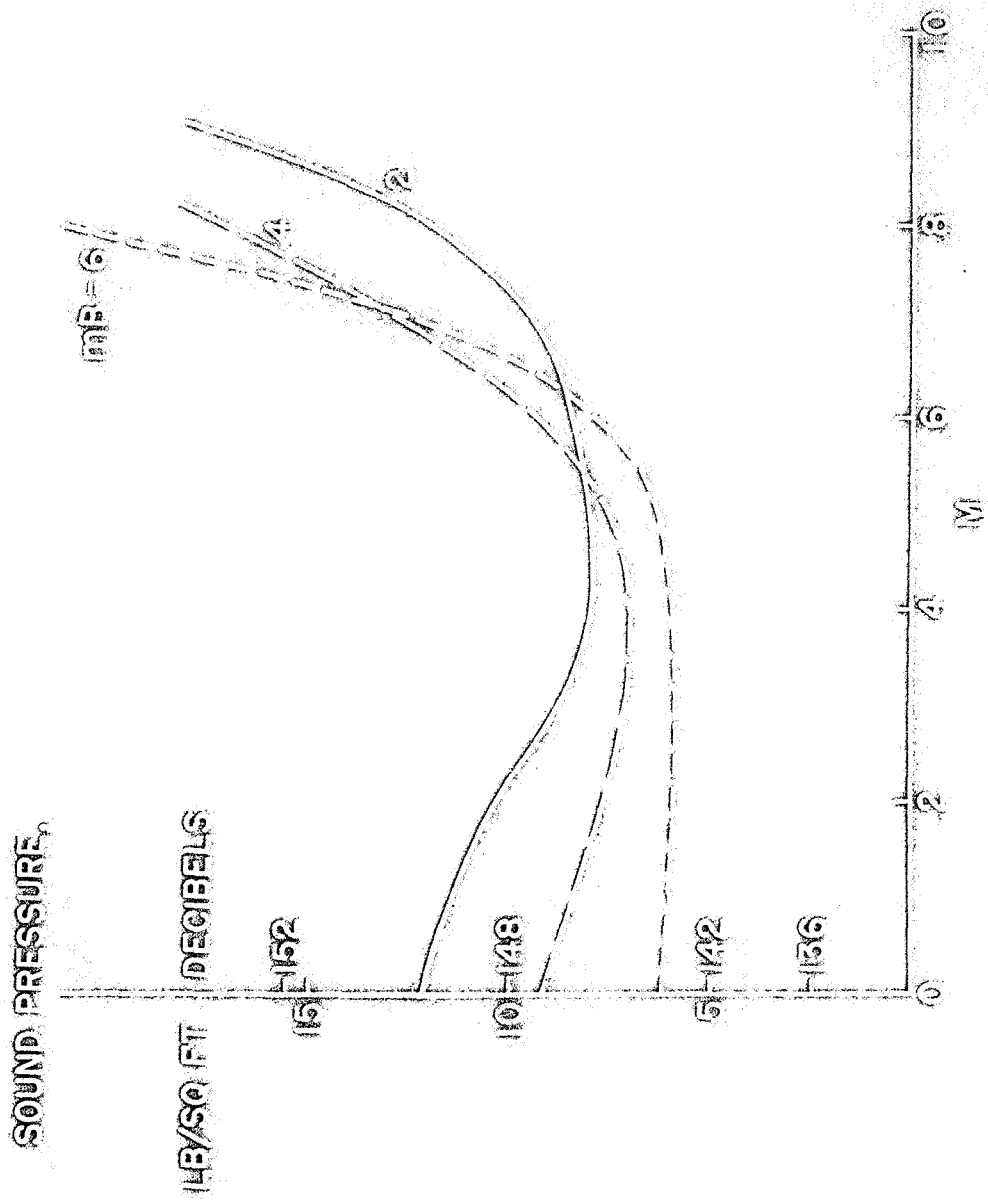


Figure 10-1. Sound pressure level (SPL) curves for various sound levels. The curves show that sound pressure level decreases as distance increases. The curves are labeled 1, 2, 3, and 4, representing different sound pressure levels. The y-axis is labeled 'SOUND PRESSURE' and 'dB/50 FT'. The x-axis is labeled 'MI'.

Figure 10. Schematic diagram of the flow pattern from a potential vortex in a fluid medium. The flow is shown in the x - y plane. The flow is shown in the x - y plane. The flow is shown in the x - y plane.

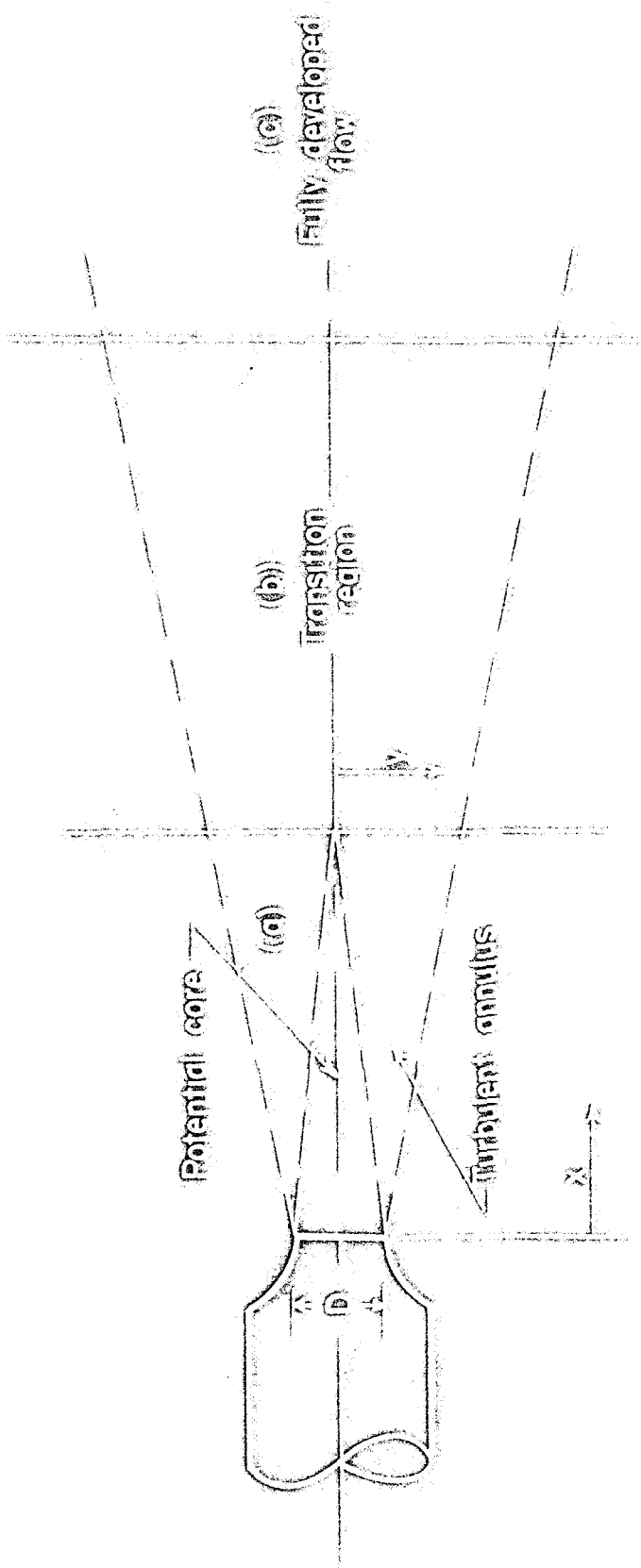
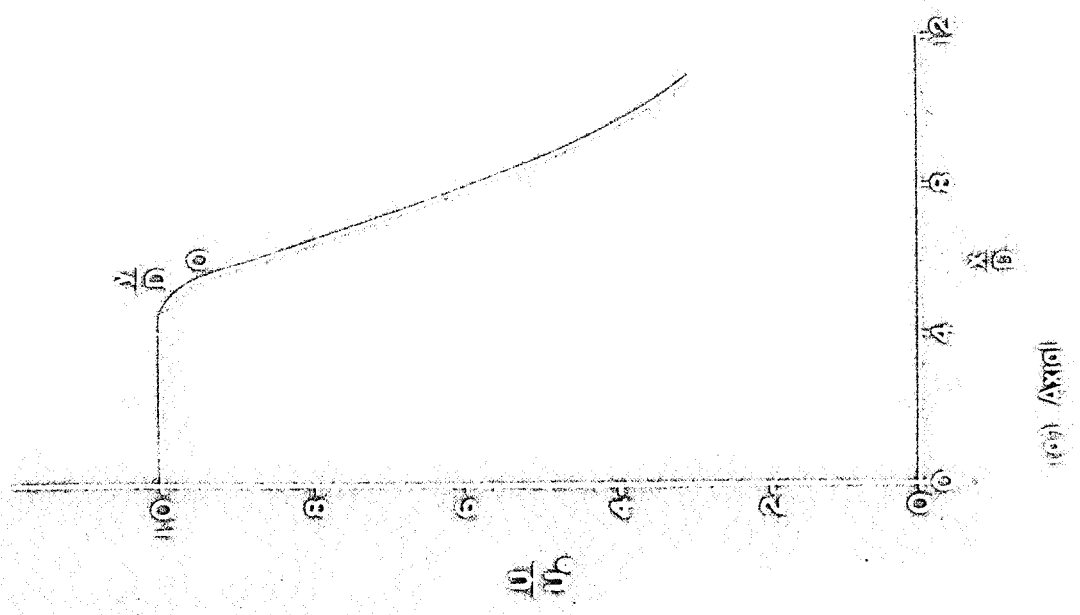
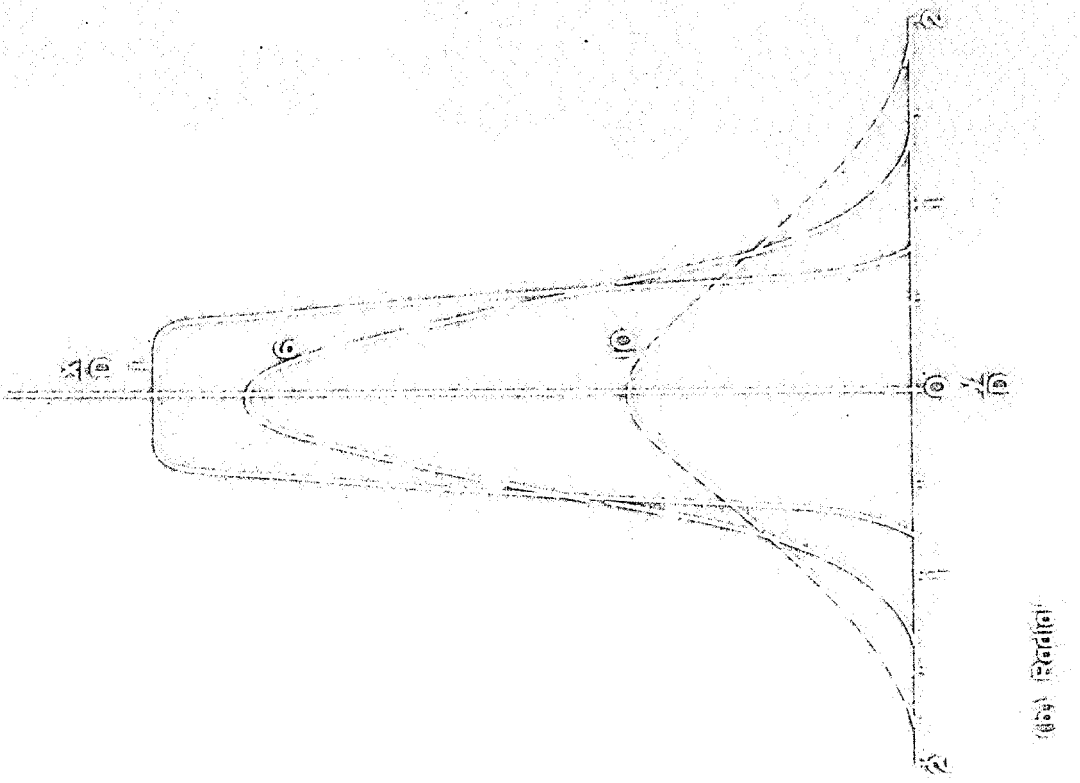


Figure 1: (a) Plot of the function $f(x)$ for $x \in [0, 1]$. The function is defined by $f(x) = \frac{1}{1+x^2}$. The plot shows a smooth, decreasing curve starting at $(0, 1)$ and ending at $(1, \frac{1}{2})$. The x-axis is labeled x and the y-axis is labeled $f(x)$.



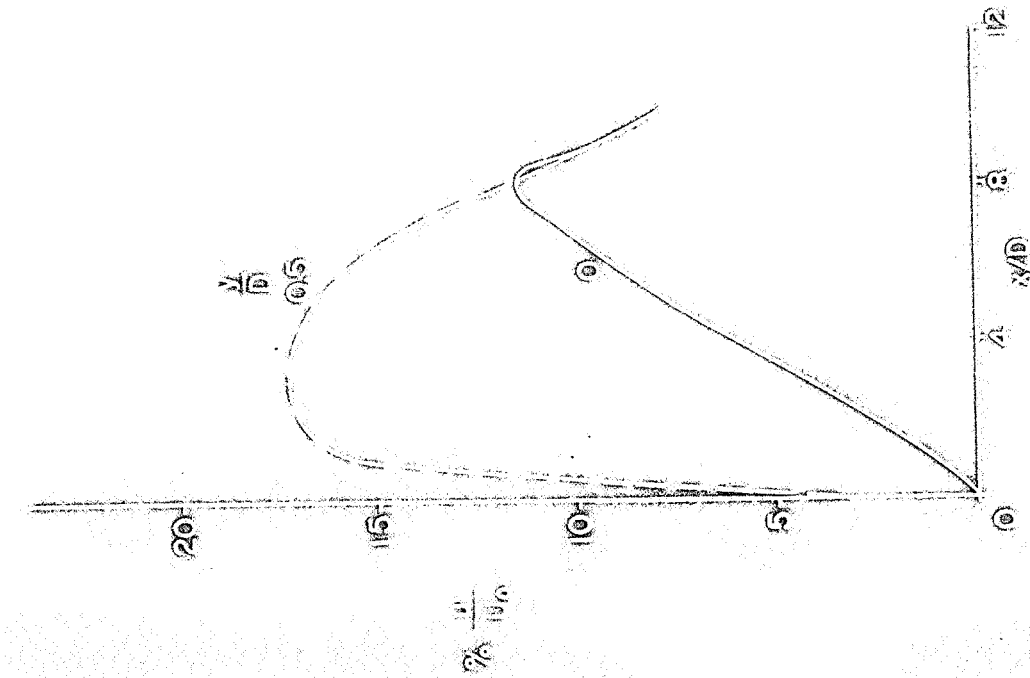
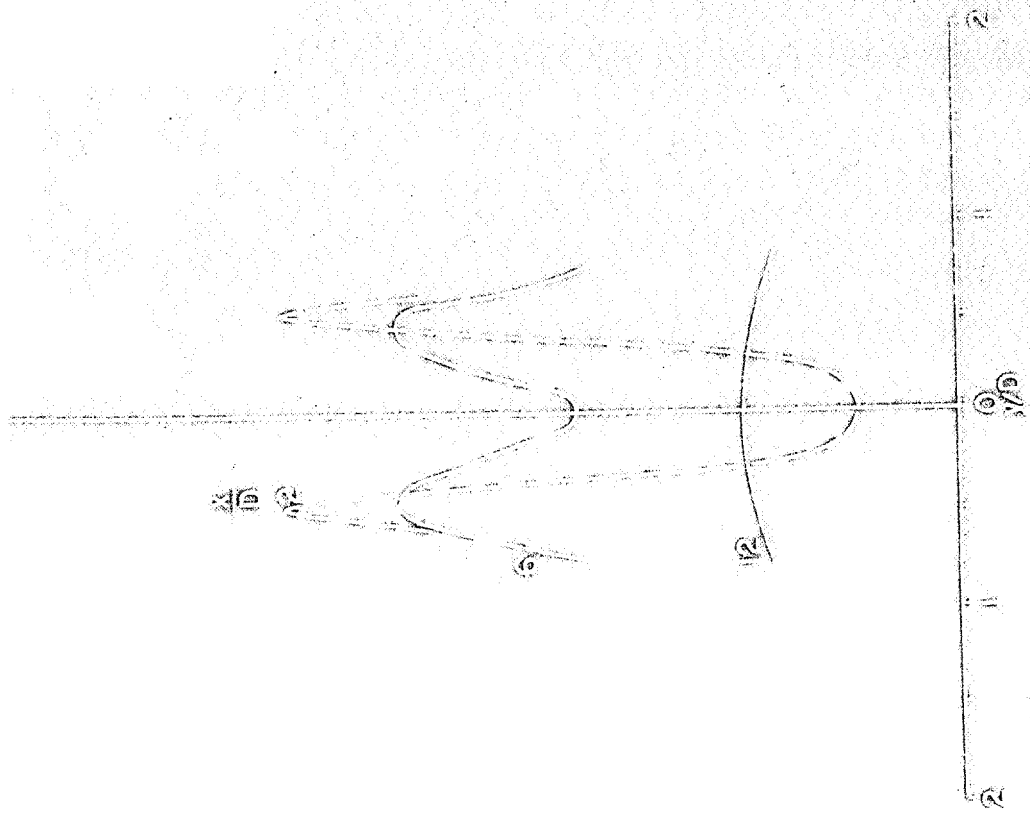


Figure 10.10: Velocity profiles in a pipe flow. (a) Axial velocity profile. (b) Radial velocity profile.

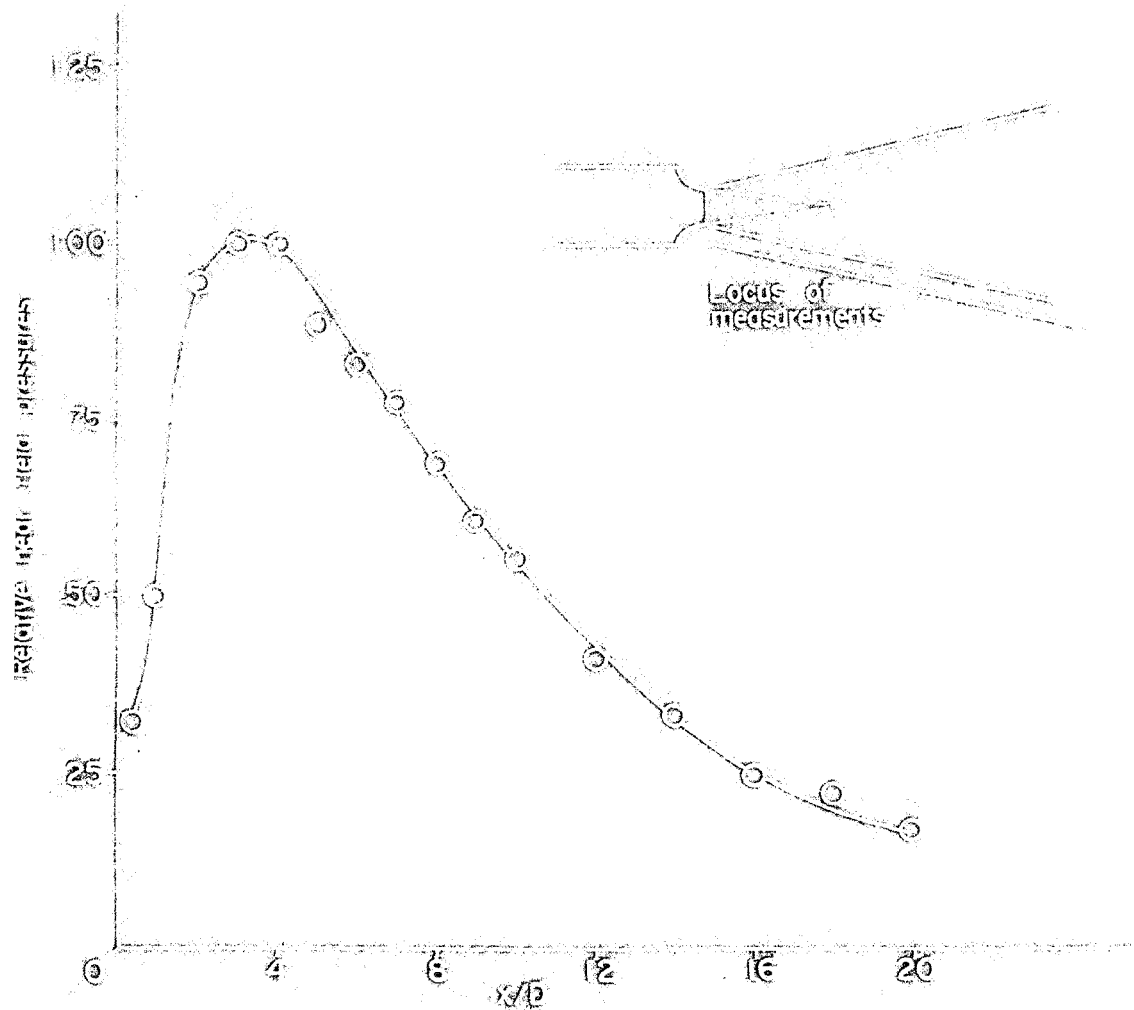


Figure 17. Relationship between percentage of ... and ...

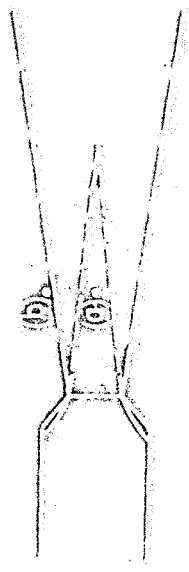
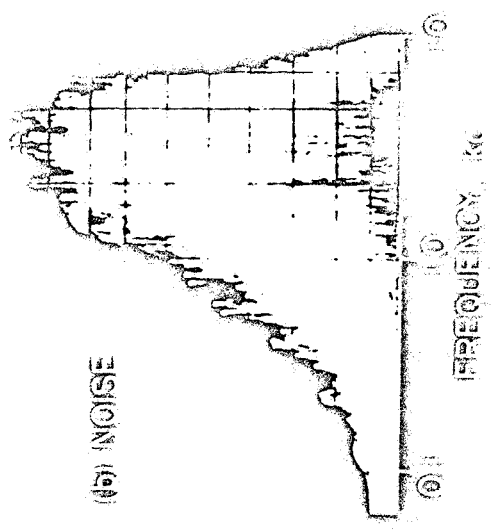
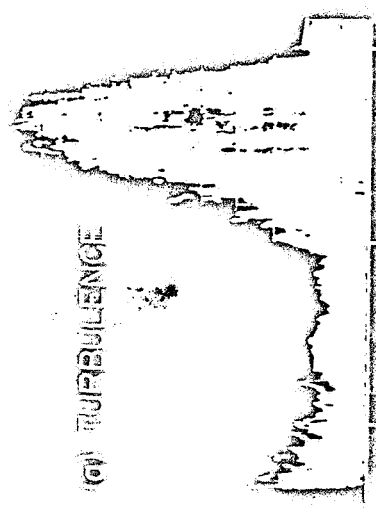


Figure 10-10. Comparison of the noise spectrum of a jet engine with the noise spectrum of a jet engine.

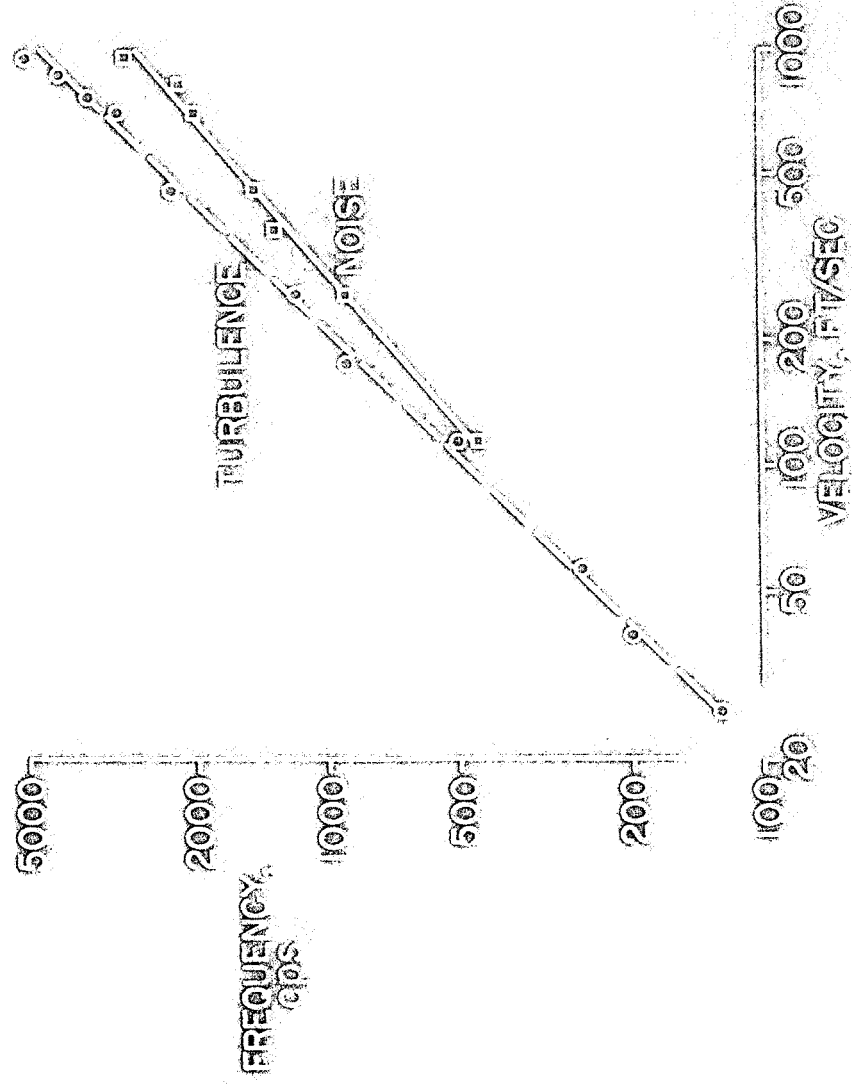
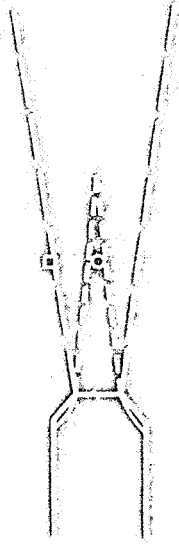


Figure 16. Comparison of noise and turbulence spectra for a typical jet engine. The noise spectrum is shown as a dashed line and the turbulence spectrum as a solid line. The noise spectrum is based on a reference level of 100 dB at 1000 ft/sec.

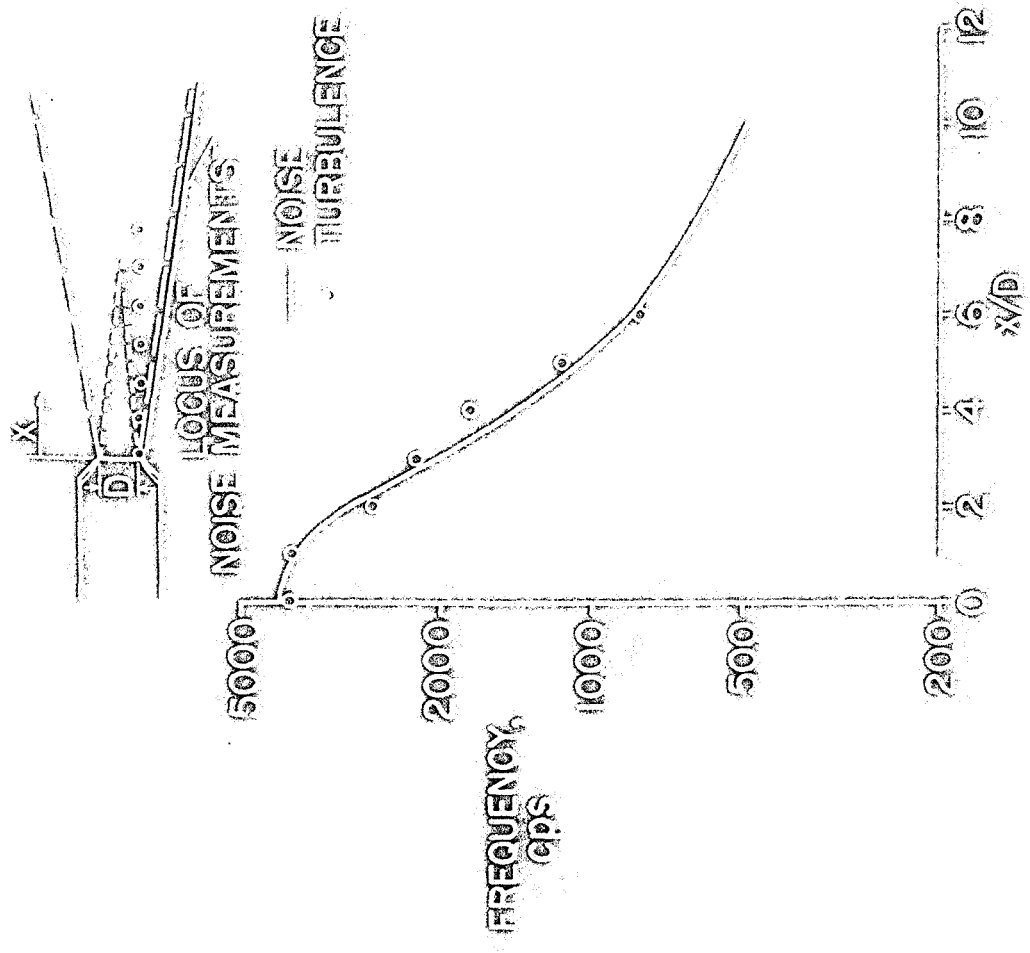


Figure 17-10. The frequency of noise due to turbulence over a propeller in an aircraft. The noise level is shown in dB on the Y-axis. The X-axis is the X/D ratio.

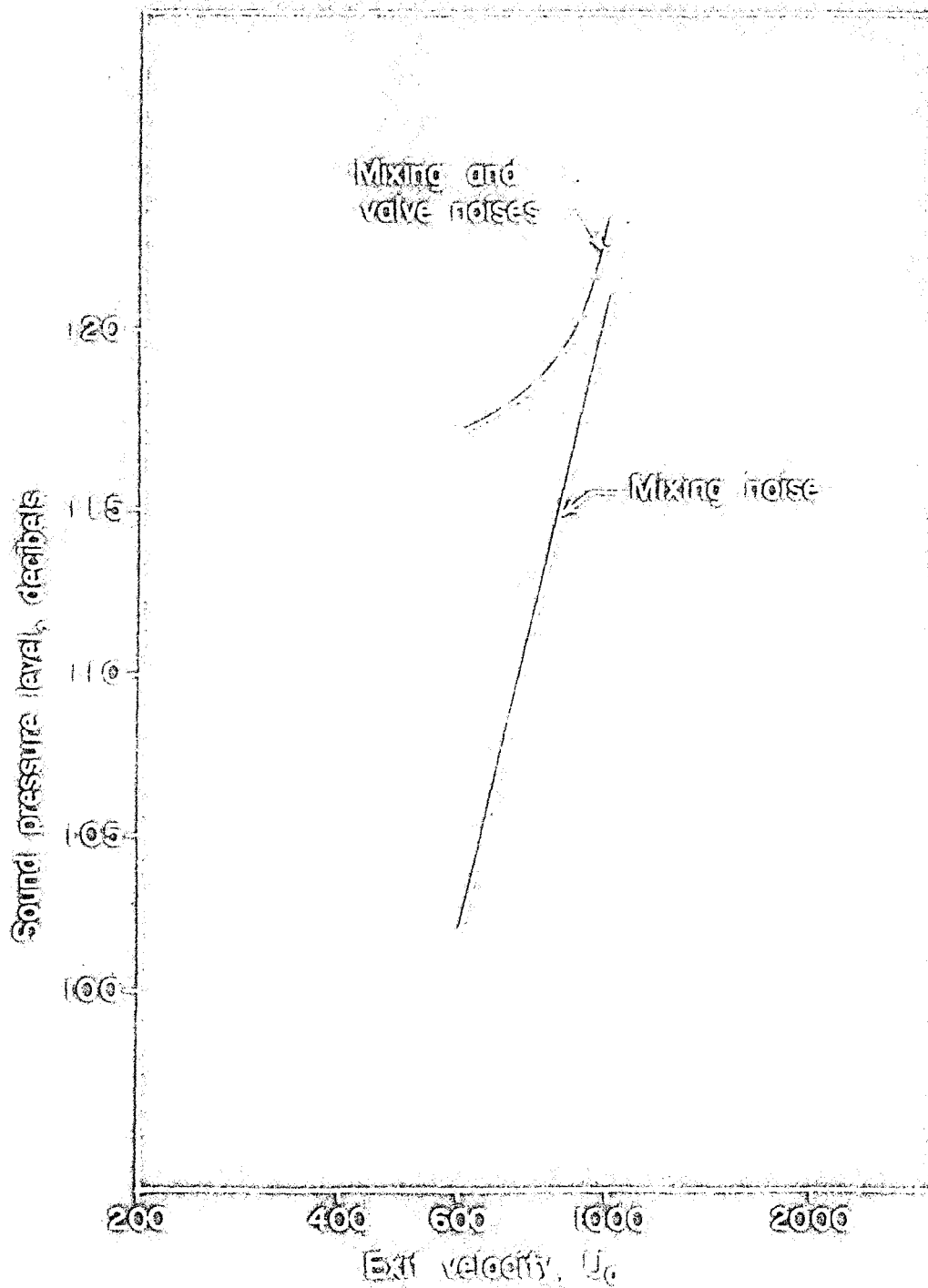


Figure 15: Sound pressure levels as a function of the exit velocity for a 3001 GE configuration in which valve noises were controlled.

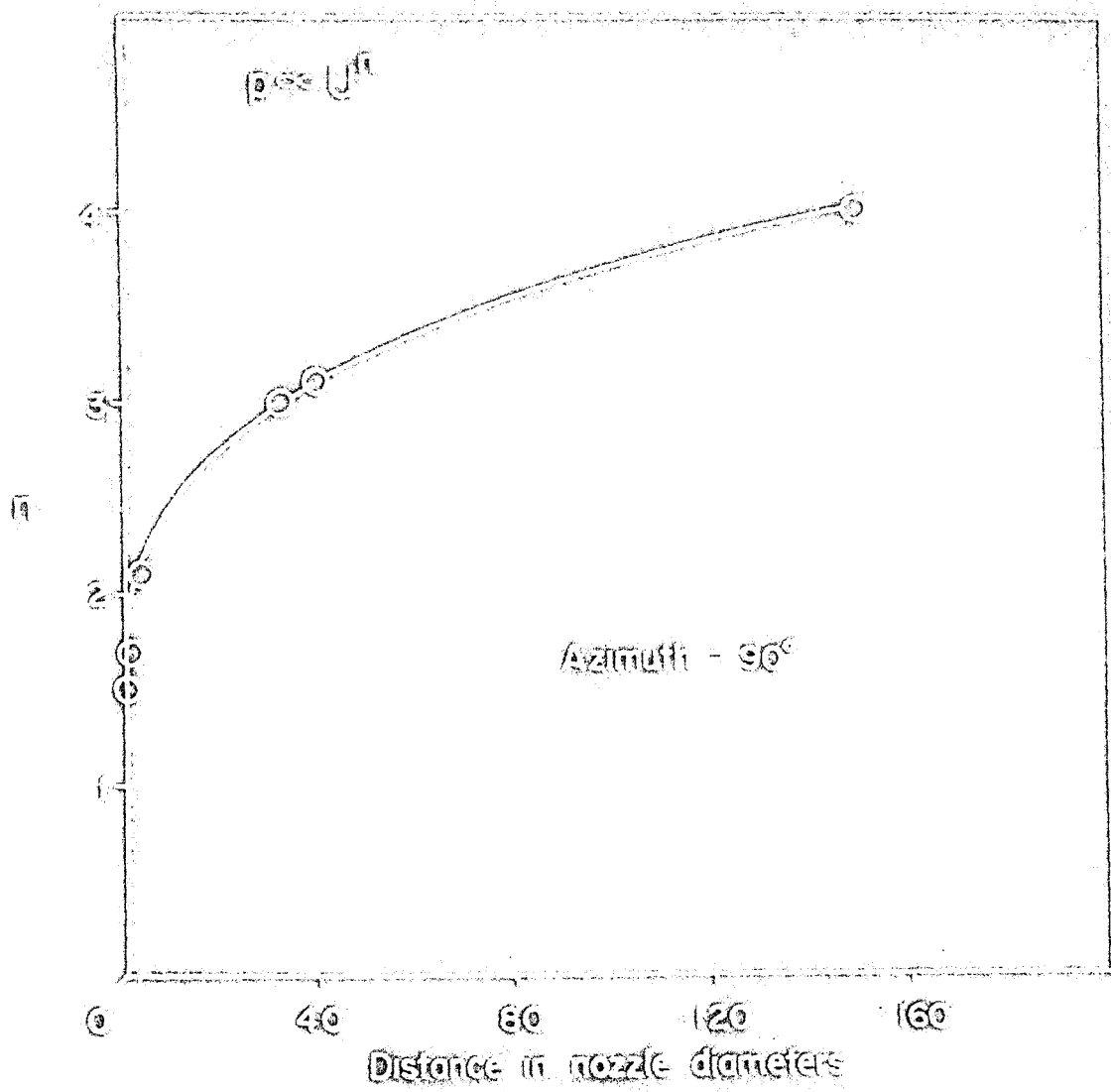


Figure 19: Variation of the absorption coefficient K as a function of distance D from the center of the jet considered. (Here distance from reference jet)

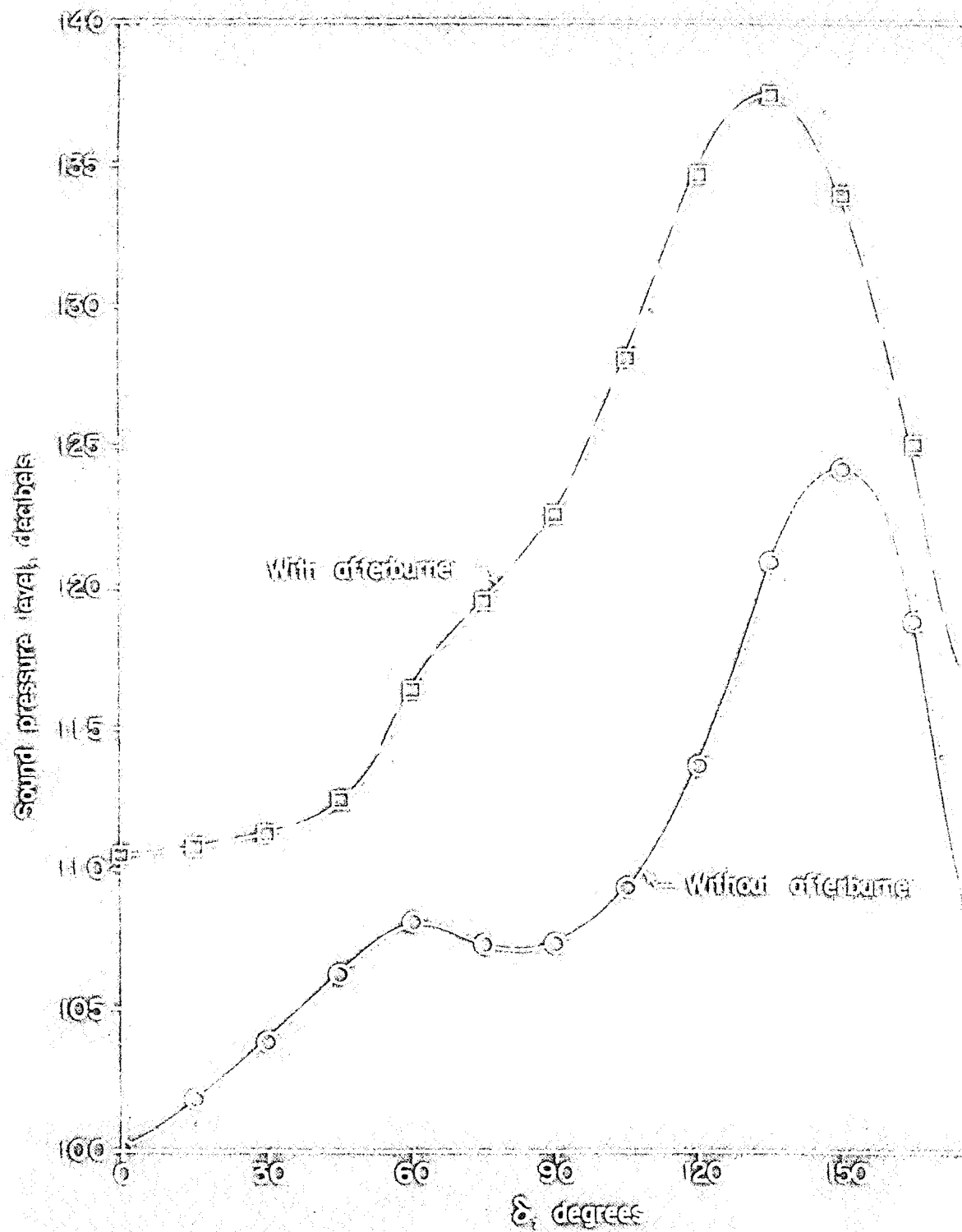


Figure 2 - Comparison of the overall sound-pressure levels at various angles for a turbojet engine with and without disturbance for a distance of 30 ft. (Data obtained from Reference 13)

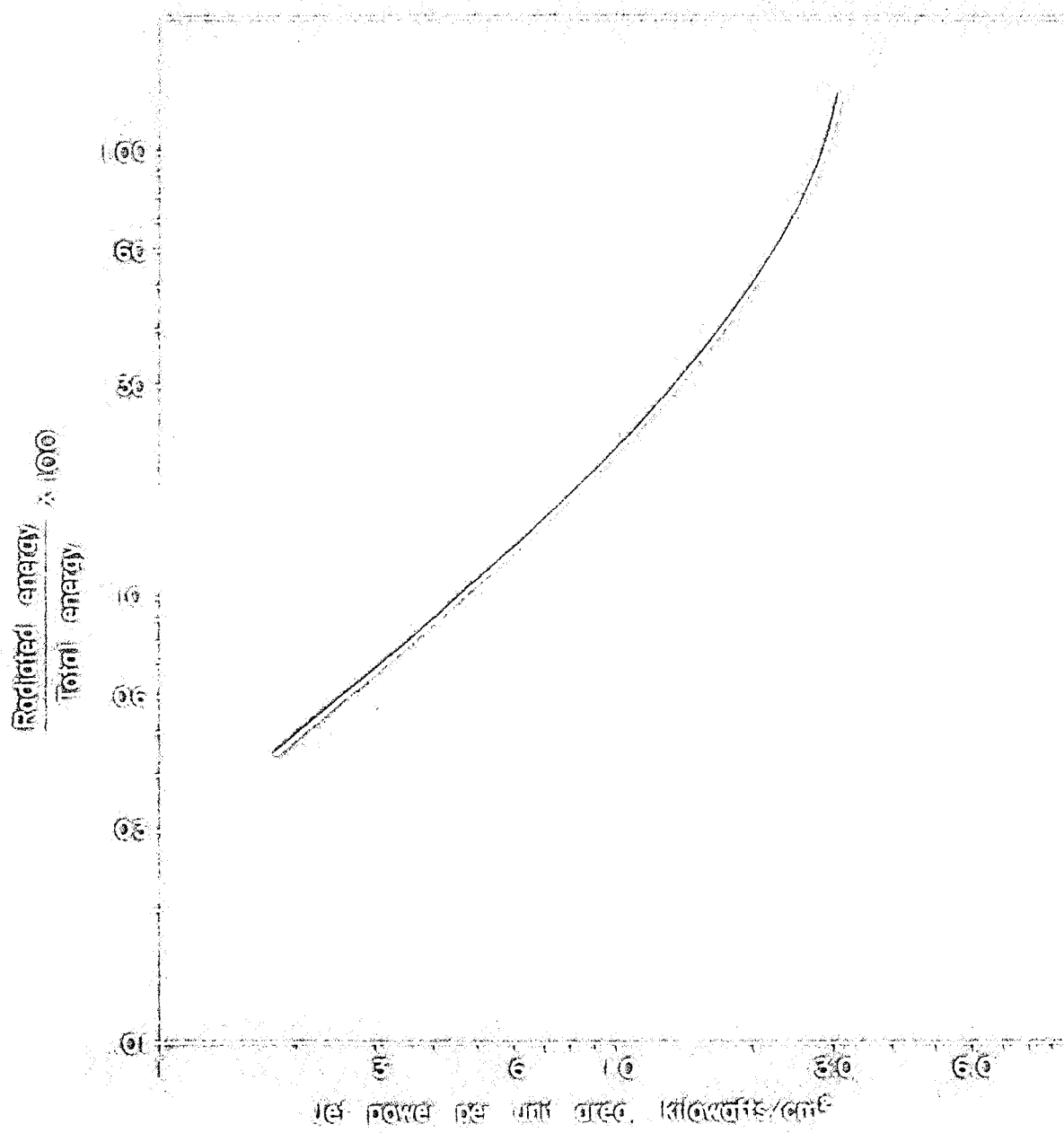


Figure 22. - Relationship between the ratio of radiated energy to total energy and the ratio of total mass to total mass. (See also Figure 17).

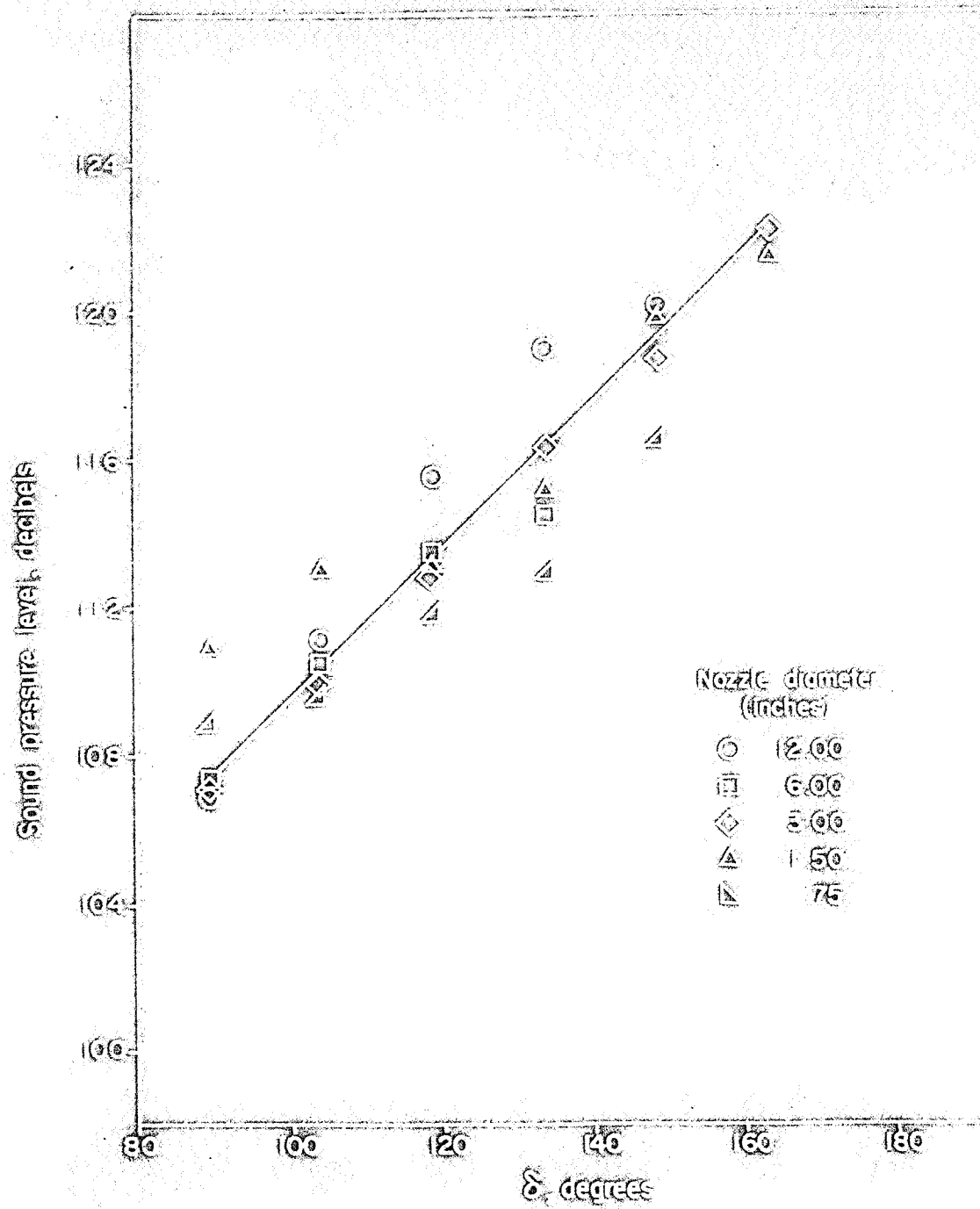


Figure 2. Sound pressure level as a function of azimuthal angle for various sizes of air jets. $U_0 = 1000$ ft/sec. $\sqrt{\rho} = 11$. Data also may be referenced to $\sqrt{\rho} = 11$.

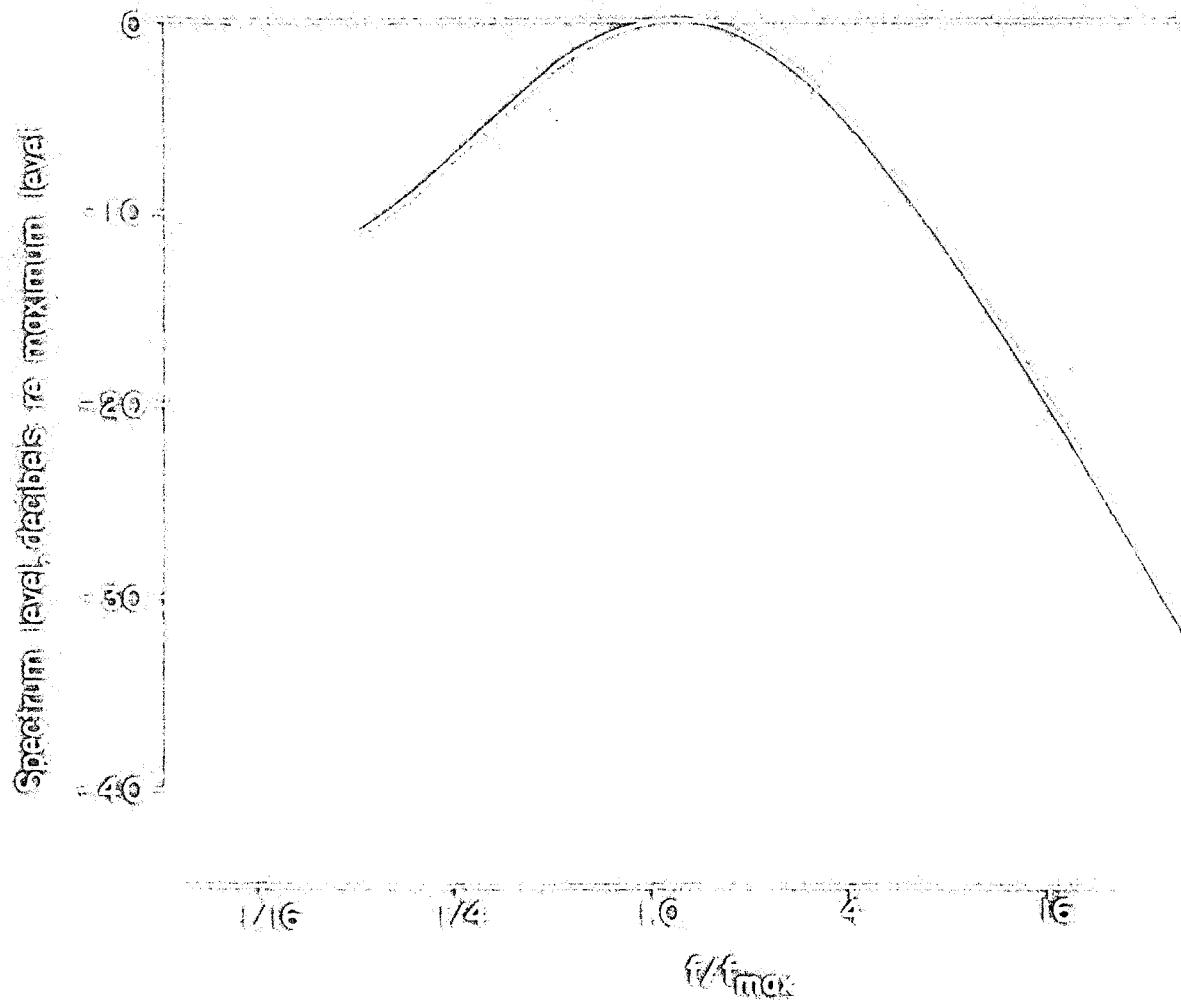


Figure 2. f_c = a frequency-derived spectrum of jet noise f_c
 (Data obtained from reference 3/4) f_c

[illegible]

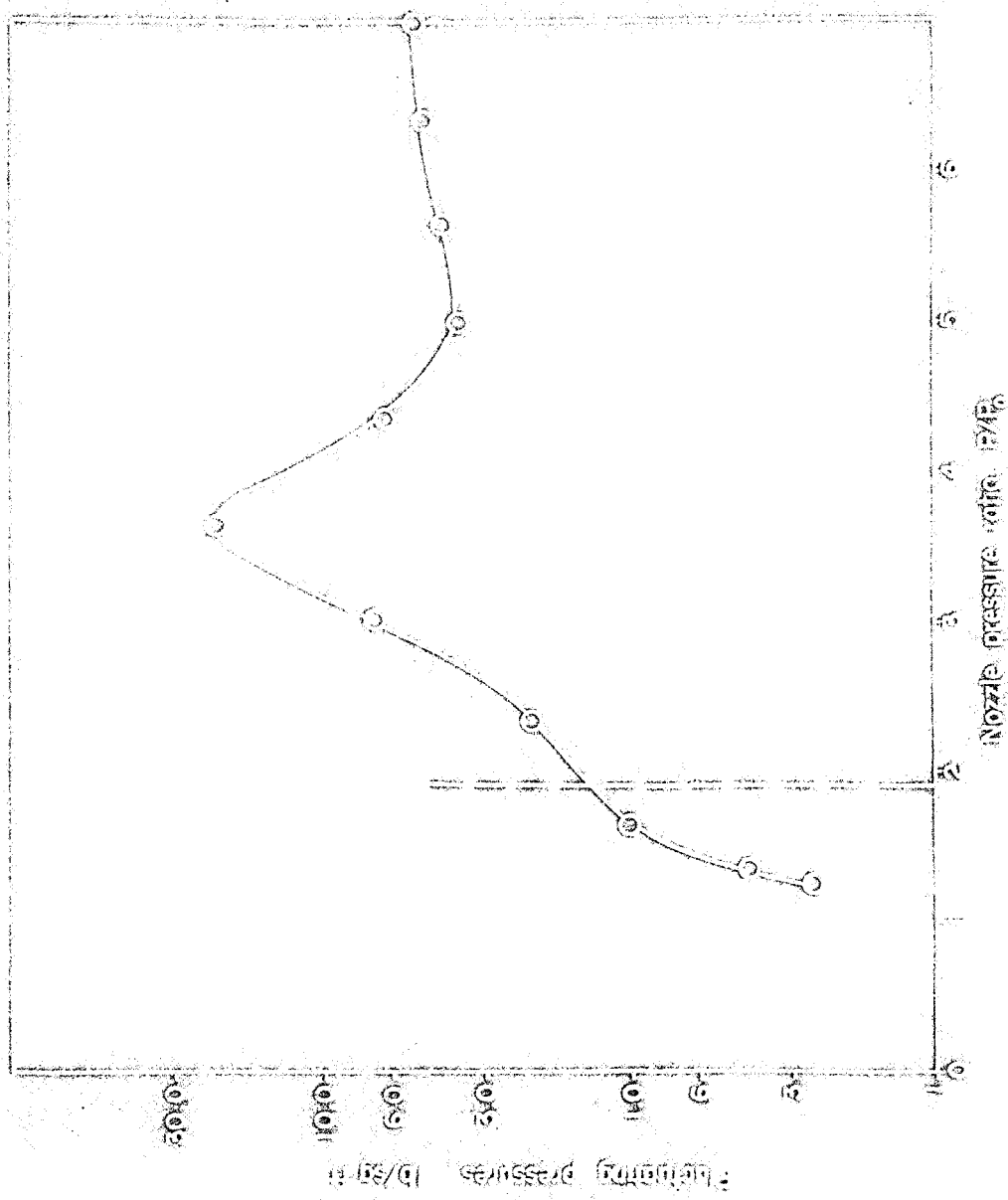
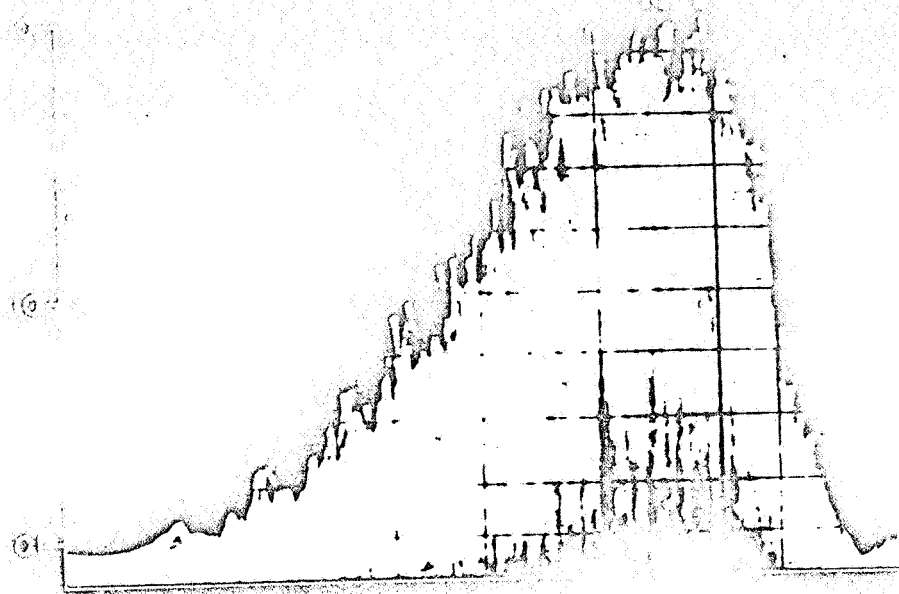
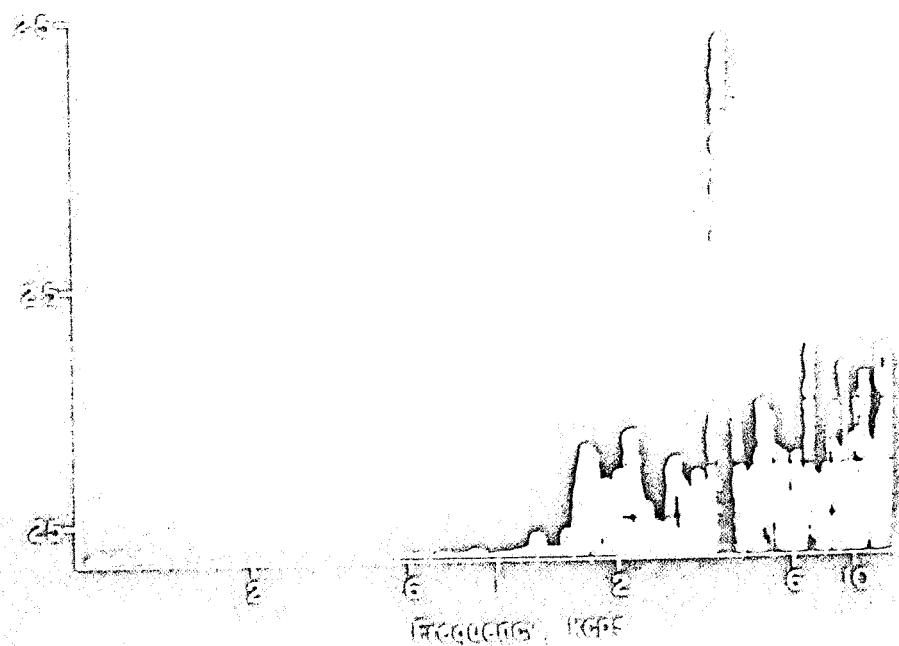


Figure 1. Jetting pressure versus nozzle pressure ratio



(a) ઉત્તરભાગ

સિગ્નલ
માહિતીઓ
10/10



(b) દક્ષિણ

સિગ્નલ માહિતીઓ: આ ગ્રાફમાં બે સિગ્નલ દર્શાવવામાં આવેલ છે. (a) ઉત્તરભાગ અને (b) દક્ષિણ. બંને સિગ્નલમાં 10/10 માહિતીઓ છે. (a) ઉત્તરભાગમાં સિગ્નલ 0.1 અને 0.2 વચ્ચે ફ્લક્ચુએટ થાય છે, જ્યારે (b) દક્ષિણમાં સિગ્નલ 0.1, 0.2 અને 0.3 વચ્ચે ફ્લક્ચુએટ થાય છે.

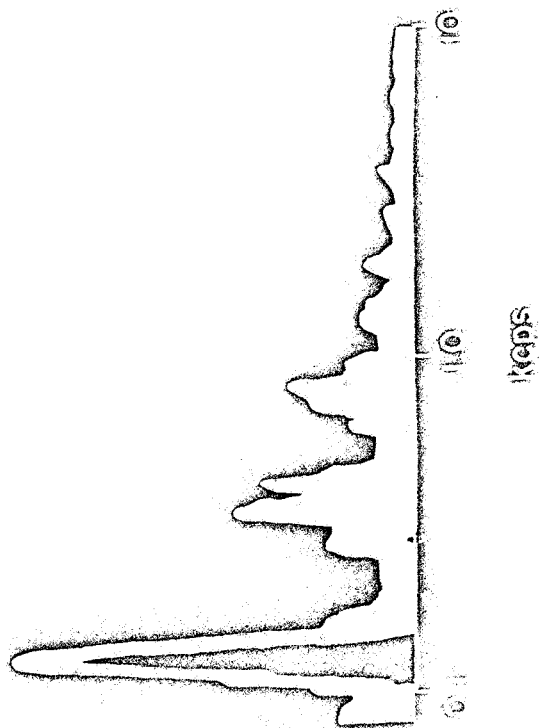
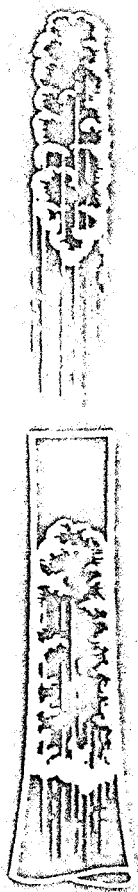
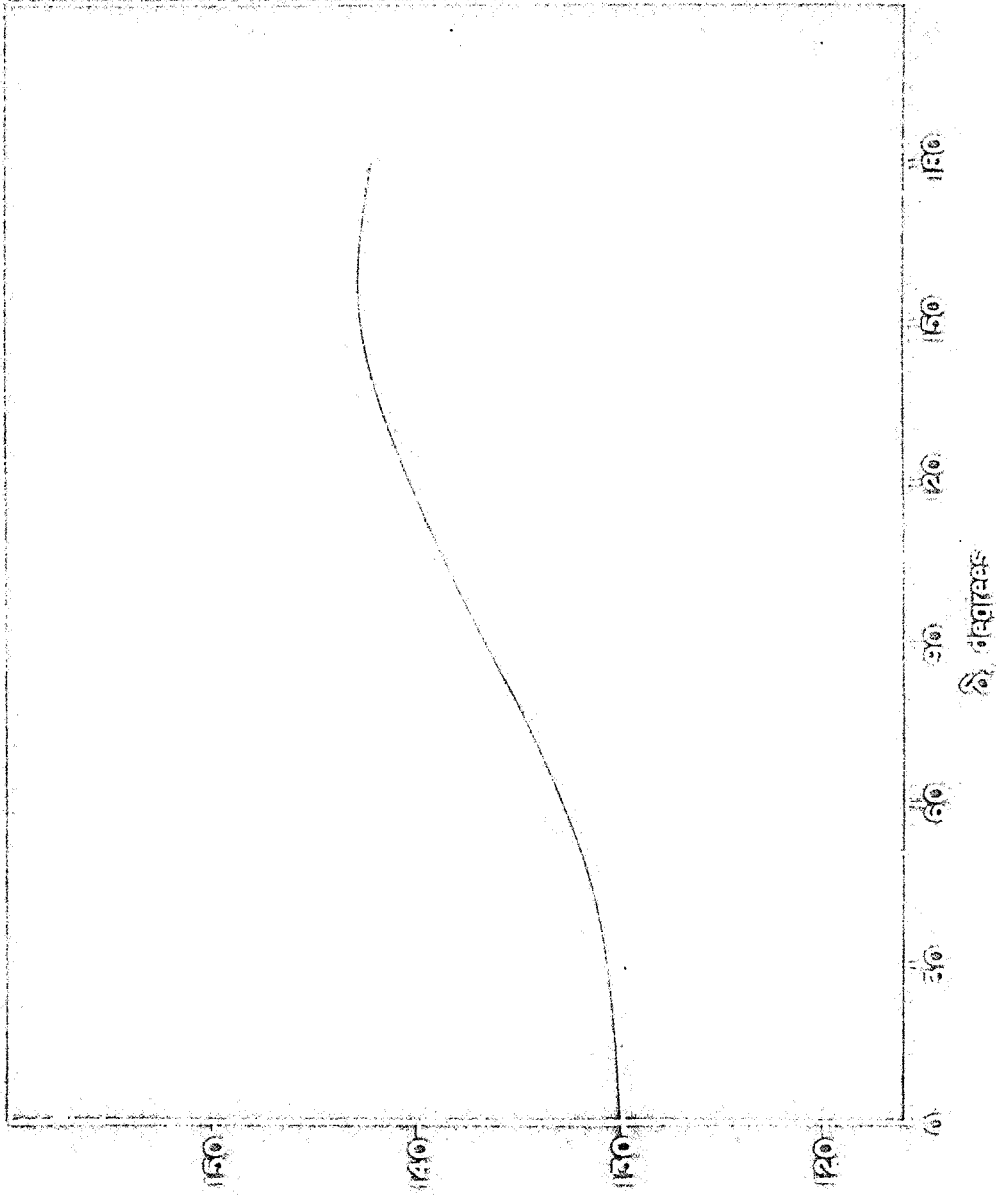
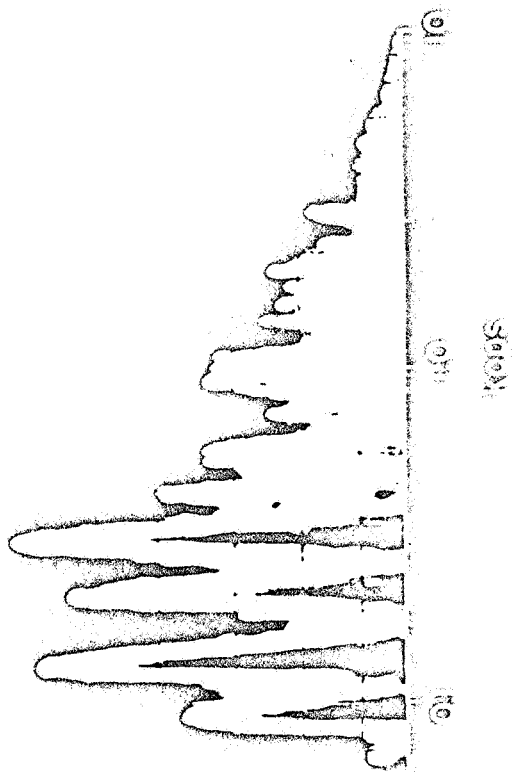


Figure 28. Spectrum and wave form of the noise from a pulsed jet engine at an azimuth angle of 90 degrees.
(Data obtained from reference 28.)

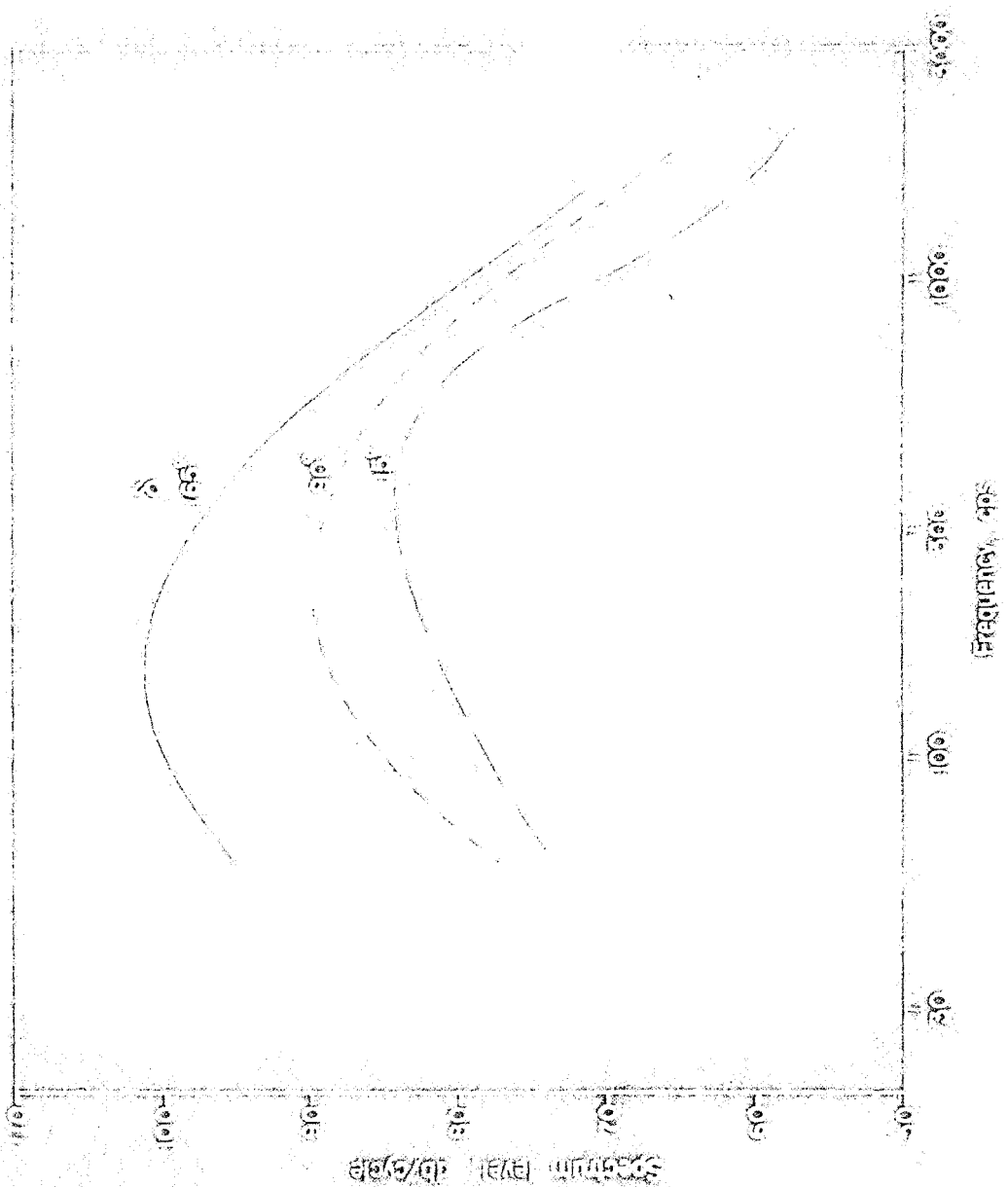


ମୃତ୍ୟୁ ହାର ଓ ତାପମାତ୍ରା ମଧ୍ୟରେ ସମ୍ପର୍କ



The figure shows a signal waveform. The x-axis is labeled 'Time' and has markers t_0 , t_1 , and t_2 . The y-axis is labeled 'Amplitude'. The waveform shows a series of sharp, narrow peaks of varying heights, followed by a period of low amplitude and then a series of smaller, more frequent oscillations.

Figure 10. - Comparison of the results of the two methods for the determination of the critical frequency.



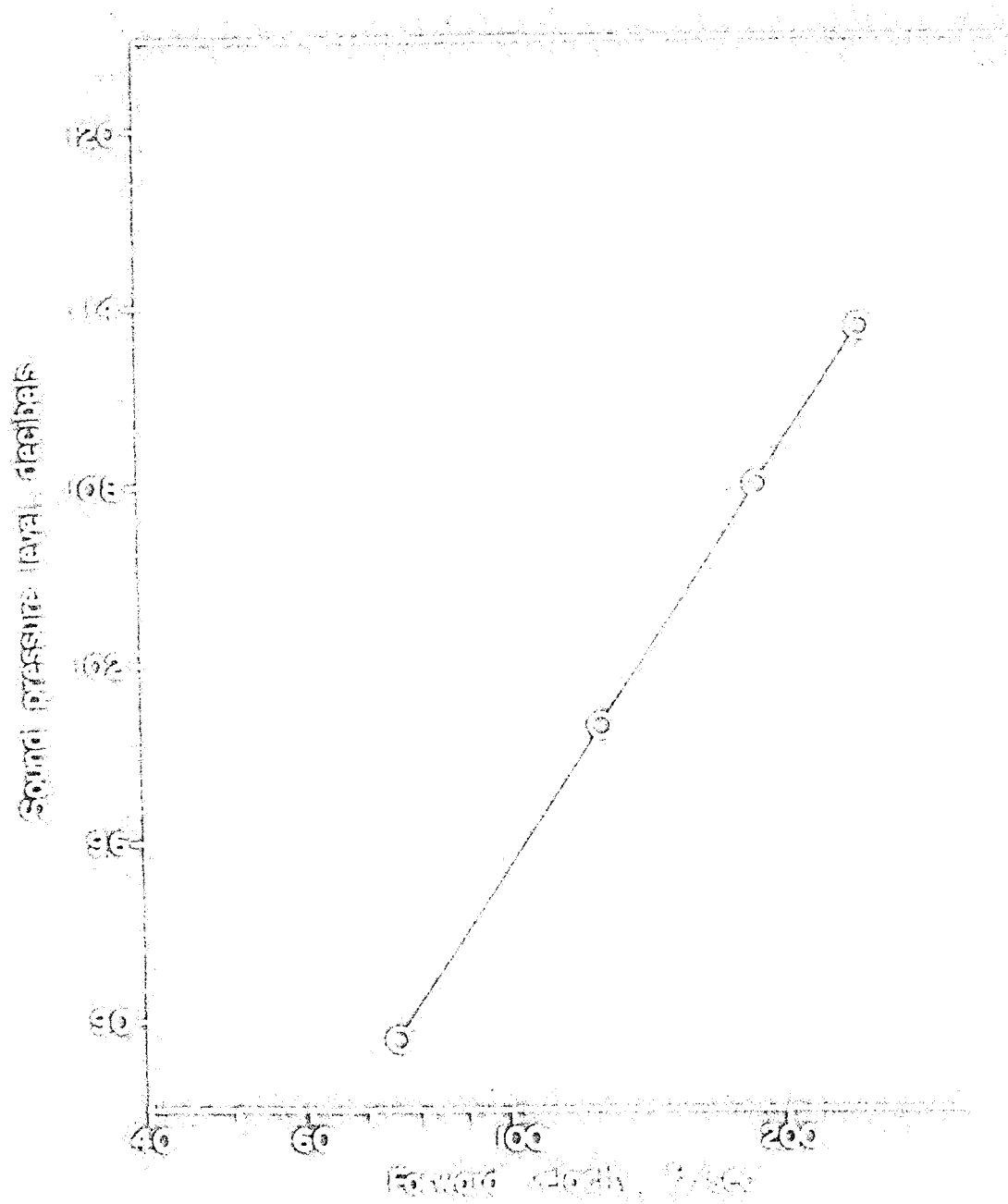


Figure 1: Relationship between sound pressure level and frequency for a sound source. The sound pressure level increases linearly with frequency.

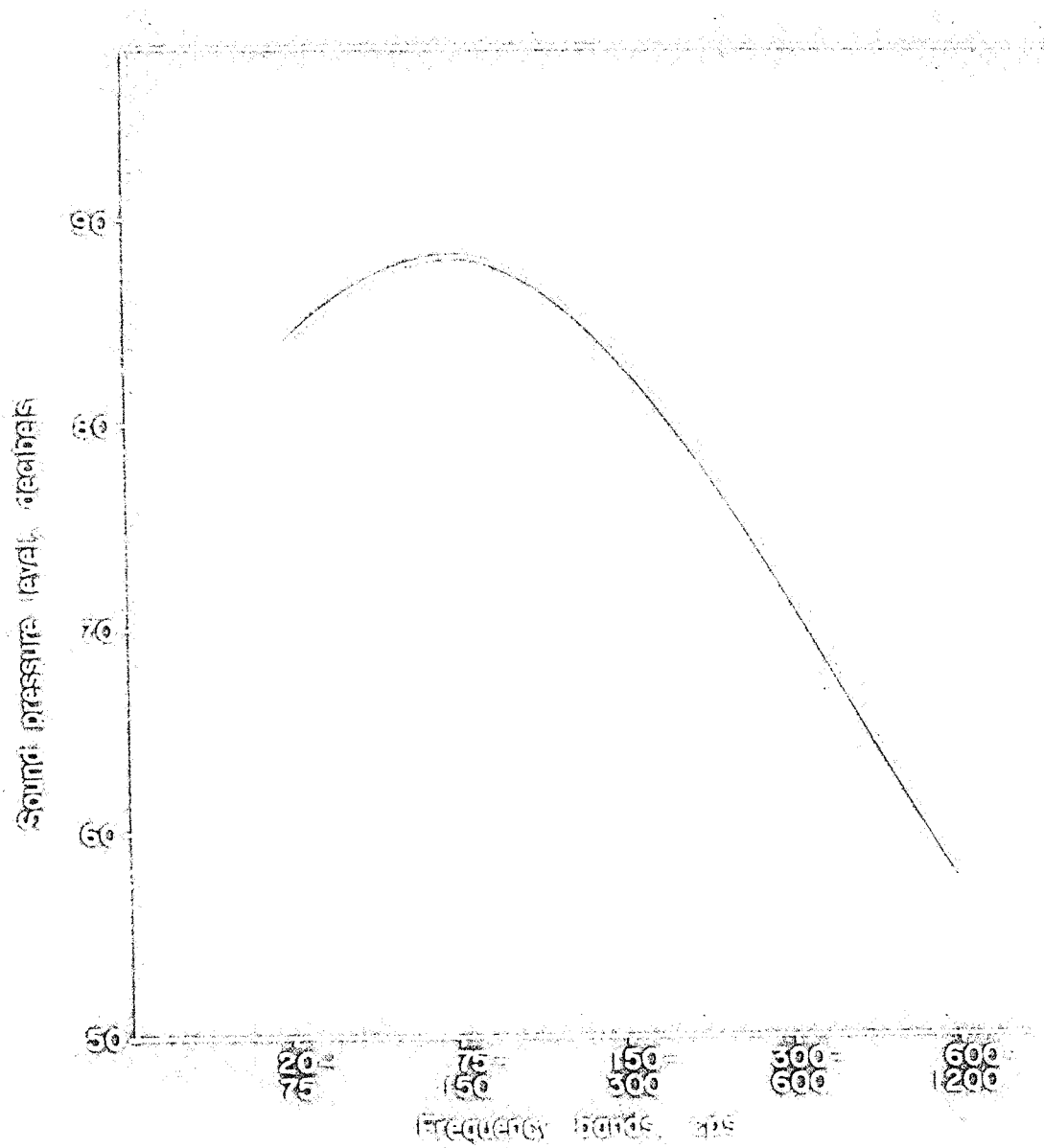
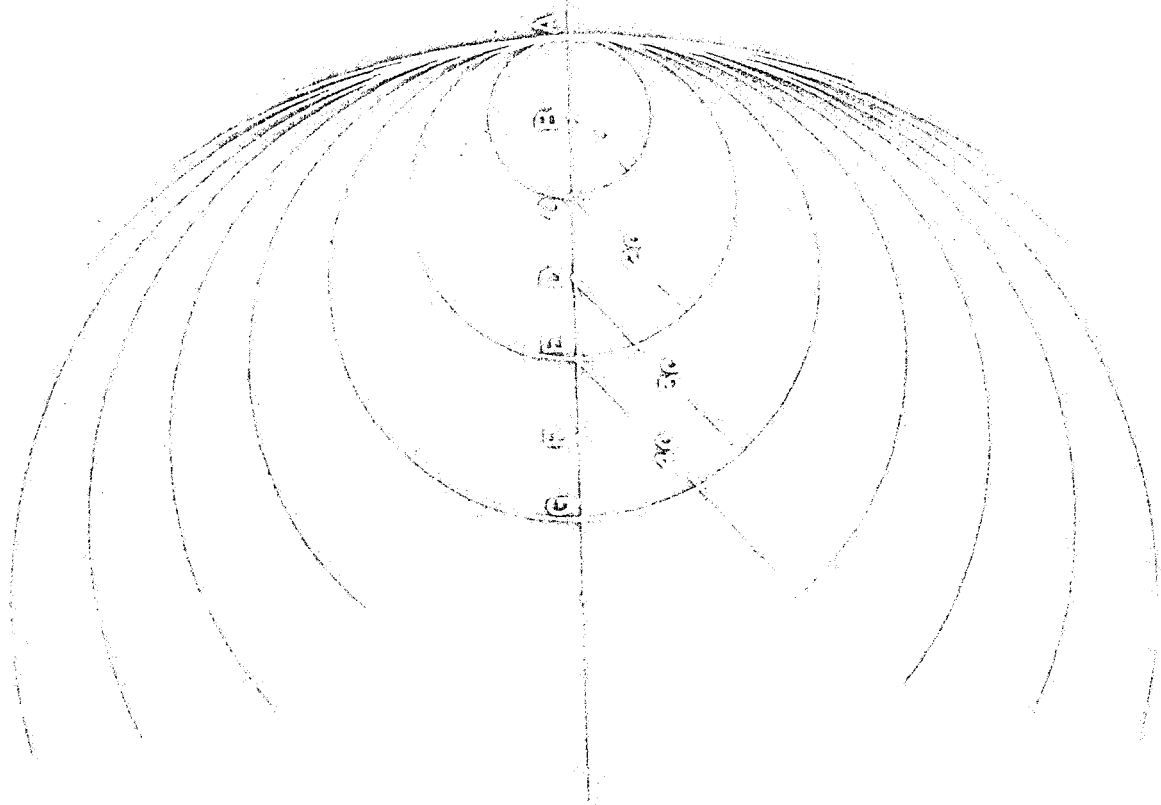


Figure 13. The adiabatic index γ is a function of the ratio of specific heats γ . The curve is a straight line for $\gamma < 1.5$ and curves downward for $\gamma > 1.5$.

Diagram of a circle



TURBOPROPPELLER ENGINE EXHAUST

RECIPROCATING ENGINE EXHAUST

PROPELLER (M, 06)

PROPELLER (M, 06)

PROPELLER (SUPERSONIC)

BY-PASS ENGINE

TURBOJET ENGINE

TURBOJET WITH AFTERBURNER

ROCKET ENGINE

RECIPROCATING ENGINE HEADROCKET

ENGINE NOT DRIVEN HEADROCKET

80

60

40

20

10

0

10

Minimum engine pressure (PSI) required

ENGINE NOT DRIVEN HEADROCKET